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March 2000 Working Group Meeting on Heavy Vehicle Aerodynamic Drag: Presentations and Summary of Comments and Conclusions

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U.S. Department of Energy

Lawrence Livermore National Laboratory

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March 2000
Working Group Meeting on
Heavy Vehicle Aerodynamic Drag:

Presentations and Summary of Comments and Conclusions

Jointly written by

Lawrence Livermore National Laboratory
Sandia National Laboratories
University of Southern California
California Institute of Technology
NASA Ames Research Center

Introduction

A Working Group Meeting on Heavy Vehicle Aerodynamic Drag was held at Lawrence Livermore National Laboratory on March 16, 2000. The purpose of the meeting was to present technical details on the experimental and computational plans and approaches and provide an update on progress in the analysis of experimental results, model developments, simulations, and an investigation of an aerodynamic device. The focus of the meeting was a review of University of Southern California's (USC) experimental plans and results, NASA Ames experimental plans, the computational results from Lawrence Livermore National Laboratory (LLNL) and Sandia National Laboratories (SNL) for the integrated tractor-trailer benchmark geometry called the Ground Transportation System (GTS) Model, and turbulence model development and benchmark simulation for a rounded cube from California Institute of Technology (Caltech). Much of the meeting discussion involved deficiencies in commercial software, needed modeling improvements, and the importance of detailed data for code validation. The present and projected budget and funding situation was also discussed.

Presentations were given by representatives from the Department of Energy (DOE) Office of Transportation Technology Office of Heavy Vehicle Technology (OHVT), LLNL, SNL, NASA Ames, USC, and Caltech. Representatives from Argonne National Laboratory also participated via telephone. This report contains the technical presentations (viewgraphs) delivered at the Meeting, briefly summarizes the comments and conclusions, and outlines the future action items.

Summary of Major Issues

There were 3 major issues raised at the meeting.

1. Our funding is inadequate to satisfy industries request for high Reynolds number experimentation and computation. Plans are to respond to the DOD and DOE requests for proposals, which require a 50-50 cost share with industry, to acquire funding for high Reynolds number experiments at NASA Ames.
2. The deficiencies in commercial software, the need for model improvements and validation, and the unavailability of a detailed database for advanced model validation needs to be recognized.
3. The need for industrial collaboration appears to be a requirement for acquiring funding.

Overview of the Project, Current Funding, and Future Workshop

Jules Routbort of DOE OHVT and Argonne National Laboratory provided an overview of the OHVT budget from fiscal year (FY) 1997 through FY00 for heavy vehicle systems aerodynamic drag reduction. For projects involving heavy vehicle systems parasitic energy losses, OHVT has requested a total of $4.5 million for FY01 with an additional $1.5 million for the solicitation of industry proposals on parasitic energy losses. The Aero Team's estimated costs for FY 2001 is over $1.5 million, because of the high cost for needed NASA experiments. This would require almost all of the OHVT's total budget for parasitic energy losses, which is not a reasonable expectation. Rather than an increase in funding, Jules presented a possible scenario for funding reduction for this project.

Jules emphasized that stable funding for our computational and experimental effort will require industrial support. Future funding through formal requests for proposals (under competitive bid) will likely require a 50-50 cost share from industry. Jules stated that commercial software companies have indicated that they can do what the Aero Team is pursuing. This comment set the tone for much debate, with the Aero Team providing evidence of needed model development, advanced computational resources, and experimental data for code validation. Without benchmarking and validation in a careful systematic approach, the correctness or accuracy of computations are unknown.

An overview of the project was presented by Rose McCallen of LLNL. The viewgraphs are enclosed. Budget issues were presented as well as the project calendar of events and plans for submitting proposals for needed funding. It was emphasized that several of the team participants (USC, Caltech, and NASA) had still not received or had just recently received the expected FY00 funds. Specifically, NASA had not received any funds and thus all testing was on hold and scheduling of tests for FY00 was in jeopardy.

It was emphasized that the program deliverables are being met only because of the team's success in leveraging funds from internal research support (e.g., LDRD and Tech Base at the National Labs) and the support of other agencies (e.g., DOD, Caltrans, NSF, ASCI) for related work.

NASA's Plans for 7-ft x 10-ft Wind Tunnel Experiments in FY00 and Future Plans for 12-ft Wind Tunnel Experiments

Jim Ross of NASA Ames presented options for the 7-ft x 10-ft wind tunnel tests which include experiments with a modified GTS model or use of a 1/8th scale model from International Transportation Corporation. NASA's plans also include provisions for USC to test their GTS model in the 7-ft x 10-ft wind tunnel for evaluation at lower blockage and higher Reynolds number flow. The purpose of all these experiments are for validation of the computational fluid dynamics (CFD) models and for further insight into truck flow phenomena.

Jim also presented details of the high Reynolds number experiments proposed for the 12-ft pressure wind tunnel. These experiments will provide answers to scaling issues as well as a database for code validation. Details are provided in the attached viewgraphs. The truck industry is very interested in these tests because they recognize that there are discrepancies between the Re effects experienced with a full-size truck and that predicted by experiment on scaled down models in wind tunnels.

The expected costs for the 12-ft wind tunnel experiments are at a 1/3rd reduced cost for a government funded effort. NASA is not charging for salaries. An additional $240K could have been saved if the experiments had been performed in FY00. The sooner these experiments can be scheduled, the less the cost. Unfortunately, DOE funds are not adequate to support these needed experiments.

Experiments with a production model in the 12-ft wind tunnel could be linked to field tests on the same geometry. This will allow for the added benefit of relating wind tunnel drag to fuel economy. However, higher Reynolds number experiments with the GTS geometry provide for an expansion of the existing database for code validation with a simplified geometry. The NASA cost estimates include the possibility of performing the experiments with both a production model and the GTS model.

Jim also mentioned an interest in using the NASA computational tools to simulate the proposed experiments. Use of the NASA code OVERFLOW was proposed. The computational tool uses a RANS approach with structured-overset grids.

USC's Wind Tunnel Tests and a Look at an Aero Device

Fred Browand of USC provided a status report of recent experiments and analysis of results. The drag results obtained in the USC wind tunnel were compared to the NASA experiments at low Reynolds number, providing explanation for any discrepancies. It was noted that the base pressure is not changing much in the low Reynolds number regime so that the drag is dominated by the front curvature. At high Reynolds number, the GTS geometry drag is all base drag so that there is significant leverage for improvement with wake conditioning.

Fred also present some preliminary results using an oscillation device to control the trailer wake flow. The device alters the turbulent structure of the wake resulting in a drag reduction. Proof-of-principal experiments are needed to determine the benefits of the oscillation device for drag mitigation.

Computational Model Development and Simulations

RANS Computations at SNL

An overview of the Reynolds-averaged Navier Stokes (RANS) computation being performed by SNL was presented by Kambiz Salari. Current efforts involve the modeling of the NASA experiments in the 7-ft x 10-ft wind tunnel.

To determine the appropriate inflow conditions for the computations, the empty tunnel was fully modeled and computed velocities were compared to those measured in the empty 7-ft x 10-ft wind tunnel. The computed and experimental velocity profiles at the test section entrance are in agreement and an adequate entrance and exit section for the computations was identified. Questions were raised as to how the pressure coefficient should be computed to be consistent with experiments.

The RANS one-equation Spalart-Allmaras turbulence model captures accurately the measured surface pressure coefficient at 0-degrees yaw for the GTS geometry. The calculations and the experiments indicate attached flow at the sides of the model for 0-degrees yaw. Some discrepancies between the computed and experimental pressure coefficient were present on the rear of the truck for 0-degrees yaw. At 10-degrees yaw, particle trace plots of the computations indicate the flow roll-up over the top of the vehicle as observed with pressure-sensitive paint (PSP) and oil-film interferometry (OIF) measurements in the wind tunnel. Details are provided in the enclosed viewgraph presentation.

Large-Eddy Simulations using the Finite Element Method at LLNL

The large-eddy simulation (LES) approach being used by LLNL was presented by Tim Dunn for both their compressible and incompressible flow models. The approach and development challenges were presented along with a progress update. Implementation of the incompressible model is complete and some validation remains. See attached viewgraphs for details on the models.

Dan Flowers of LLNL presented preliminary results using the compressible model for the GTS geometry for 0.3 and 2.4 million elements at 0-degrees yaw. A method for ease in grid refinement by using a separate near-body grid that boxes the vehicle was also presented. The computations with the course grid indicate higher drag results than measured, however, grid refinements show a trend towards the experimental results. The computed dominate pressure frequency with the 0.3 million element grid compares to that measured with the unsteady pressure probe mounted on the rear of the GTS. Further details are provided in the enclosed viewgraph presentation.

Simulations using Vortex Methods: A Gridless Technique

The Caltech group continues to improve their fast, parallelized, adaptive vortex method. Current activities at Caltech include: incorporating bodies with arbitrary complexity, obtaining higher Reynolds numbers computations, and developing and analyzing subgrid models for large-eddy simulation. Mark Brady of Caltech provided an overview of the vortex method approach and described a new technique for incorporating arbitrary sized body-surface triangles which has been recently implemented. This technique maintains computation accuracy while improving performance. Also a geometry definition similar to the GTS model (cab and trailer) has been defined and tested. Simulation Reynolds numbers are still quite low but plans are to move into the higher Reynolds number regime with the addition of subgrid scale models. Tony Leonard of Caltech presented his work in developing subgrid scale models for near-wall turbulence for use with large-eddy simulation. Several approaches for subgrid modeling for turbulent boundary layers have been identified for further developement.Further details and results of computations with the vortex method code and on the turbulence modeling approach are in the attached viewgraphs.

Future Meetings

The next Working Group Meeting will likely be in July or August 2000. The location of the next meeting has not yet been established.

Action Items

The follow-on action items with the individuals responsible for the tasks are as follows:

Response to DOD and DOE request for proposals (R. McCallen)

Proposal submission to BES and NSF (F. Browand and A. Leonard)

Paper and presentation at SAE Government Industry Meeting in Washington, DC in June 2000 (R. McCallen)

Meeting report with viewgraphs (R. McCallen)

Quarterly report due April 15, 2000 (R. McCallen)

Establish location and schedule next working group meeting (R. McCallen)

Truck Aero Team Meeting

LLNL, Livermore, CA

March 16, 2000

Attendee List

Attendee	Organization	e-mail address and phone
Tom Arledge	NASA	tarledge@mail.arc.nasa.gov, 650-604-1604
Mark Brady	Caltech	mbrady@caltech.edu, 626-395-3285
Fred Browand	USC	browand@spock.usc.edu, 213-740-5359
Tim Dunn	LLNL	tdunn@llnl.gov, 925-422-8258
Dan Flowers	LLNL	flowers4@llnl.gov, 925-422-0529
Esther Ku	DOE	esther.ku@oak.doe.gov, 510-486-4297
Tony Leonard	Caltech	tony@galcit.caltech.edu, 626-395-4465
Rose McCallen	LLNL	mccallen1@llnl.gov, 925-423-0958
Jerry Owens	LLNL	jlowens@llnl.gov, 925-422-1646
Jim Ross	NASA	jcross@mail.arc.nasa.gov, 650-604-6722
Jules Routbort	ANL/DOE	routbort@anl.gov, 630-252-5065
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Kambiz Salari	SNL	ksalari@sandia.gov, 505-844-9836
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Agenda

Heavy Vehicle Aerodynamic Drag: Working Group Meeting

Lawrence Livermore National Laboratory

Livermore, CA

Wednesday, March 16, 2000

Purpose of Meeting

Discussion of project technical and budget issues and proposed strategies to improve budget situation

Review of experimental and computational plans

Presentation of technical details of experimental and computational work in progress

Introduction to LLNL and Energy Directorates	**Ray Smith**
OHVT and budget	**Jules Routbort**
Introduction and issues	**Rose McCallen**
NASA data reduction/analysis/documentation and test plans	**Jim Ross, Bruce Storms, Tom Arledge**
USC test results/plans and a look at aero devices	**Fred Browand**
SNL RANS computations/analysis and DES development	**Kambiz Salari, Walt Rutledge**
Overview of TMC meeting	**Frank Tokarz**
LLNL LES compressible/incompressible computations/analysis	**Tim Dunn, Dan Flowers, Jerry Owens, Rose McCallen**
Caltech vortex method development and computations	**Tony Leonard**
Demonstration project: description and status	**Ross Sheckler**

Discussion:

Outline strategies/plans for resolving budget issues
Review computational/test plans for completeness
Discuss needed task expansions (e.g., design aspect) and research for project success
Decide on best collaborative approach with software industry and tractor manufacturers

Aerodynamic Design of Heavy Vehicles

- Overview of Project
- Budget Issues

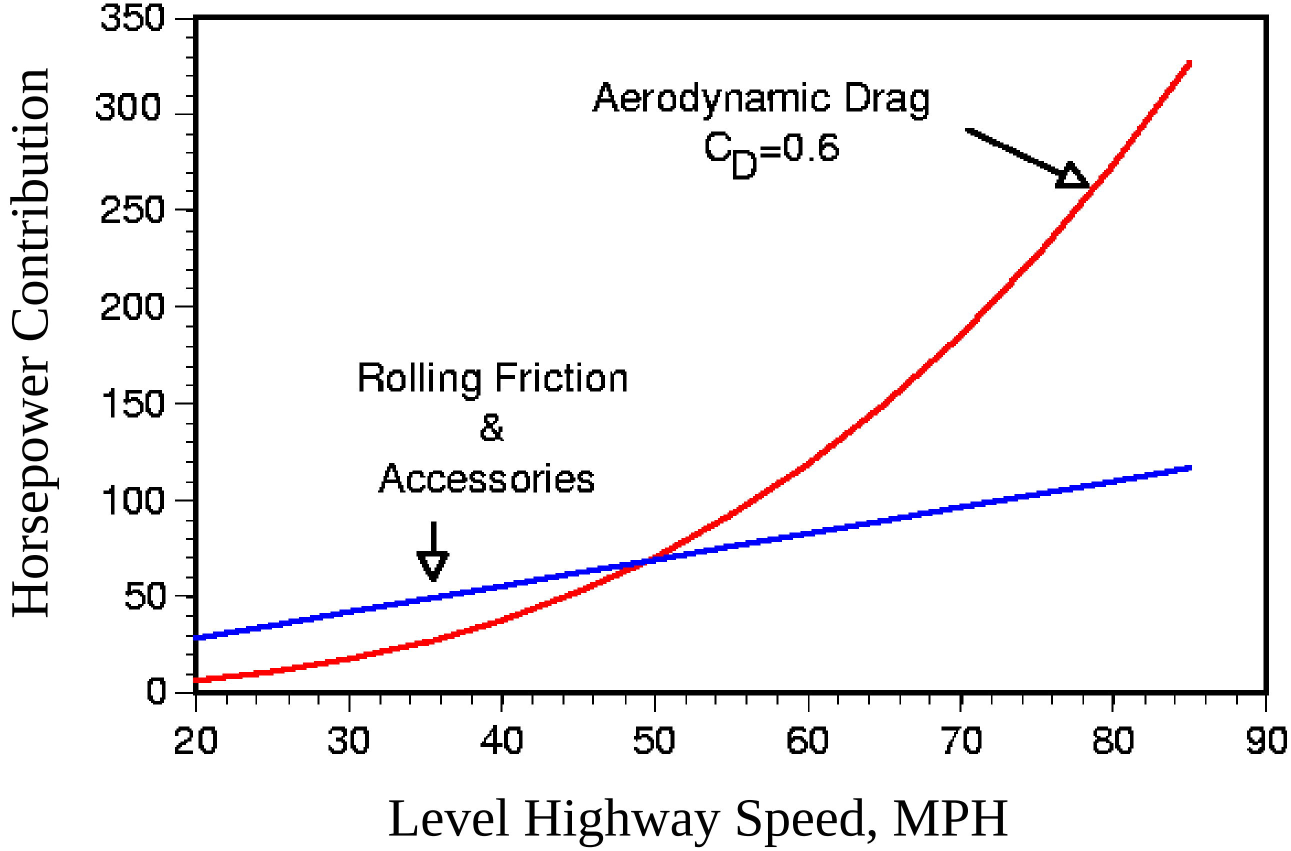
Rose McCallen

Lawrence Livermore National Laboratory, Livermore, CA

March 16, 2000

At 70 mph, 65% of the total energy expenditure is in overcoming aerodynamic drag.

Typical Class 8 tractor-trailer



Reducing aerodynamic drag has a higher potential leverage than any other technology improvement.

20 Year Projection

Technology	Fuel Reduction
Improve engine efficiency by 8%	8%
Weight reduction of 15%	< 10%
Reduce aerodynamic drag by 25%	10 - 15%

Kenworth cab-over-engine (1990)

Kenworth T2000 conventional model (1999)

The truck industry relies on wind tunnel and field experiments for aerodynamic design and analysis.

Wind Tunnel Testing

Costly detailed models

Expensive tunnel use

Trial-error approach to determine drag effects

Cabover Engine

Conventional

Field Testing

Performed by both manufacturer and fleet operators

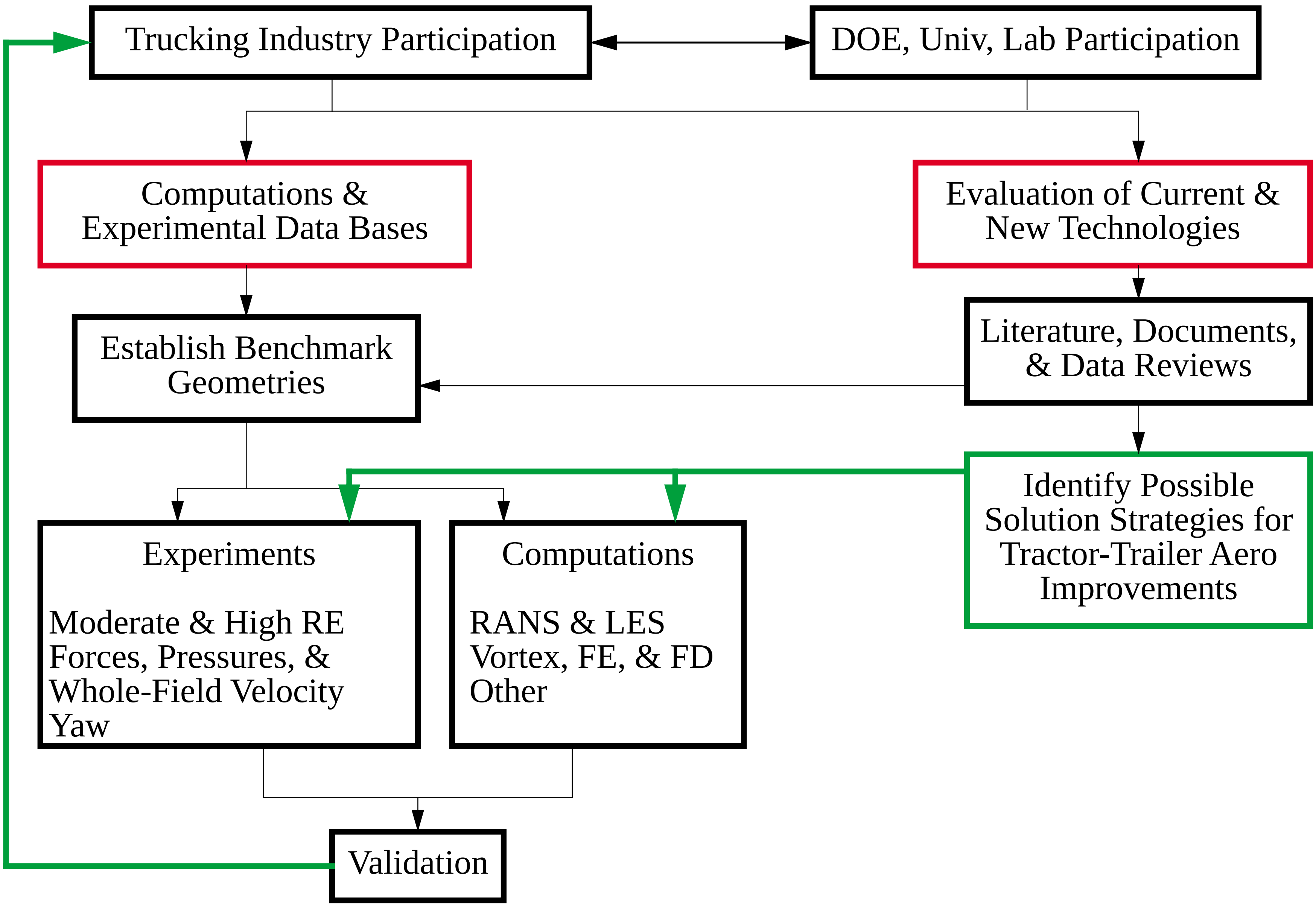
Issues

A tractor is paired with several different trailers

Almost no aero design interaction between tractor and trailer manufacturers

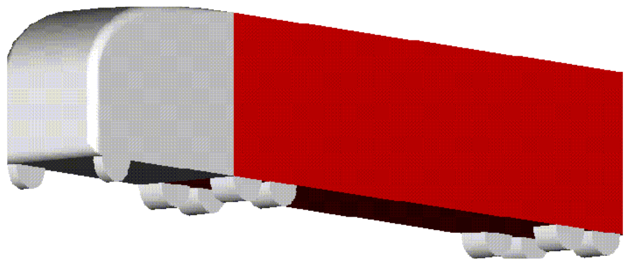
The effects of design changes on drag are not well understood and computational guidance is needed

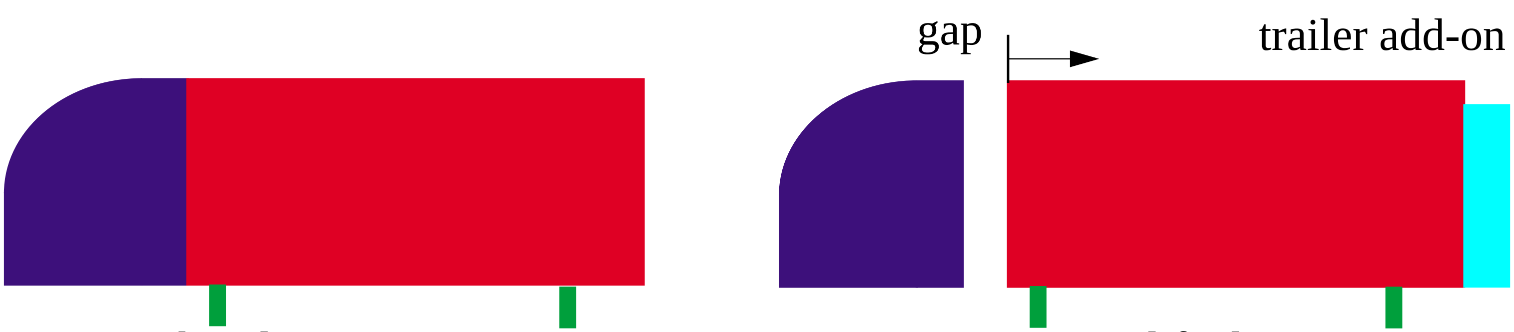
The current project focus is on a validated simulation capability, but the MYPP includes a 'design' effort.



To obtain near-term results on a limited budget, we chose a simple geometry with existing data and modeling.

Ground Transportation System (GTS)





baseline GTS

modified GTS

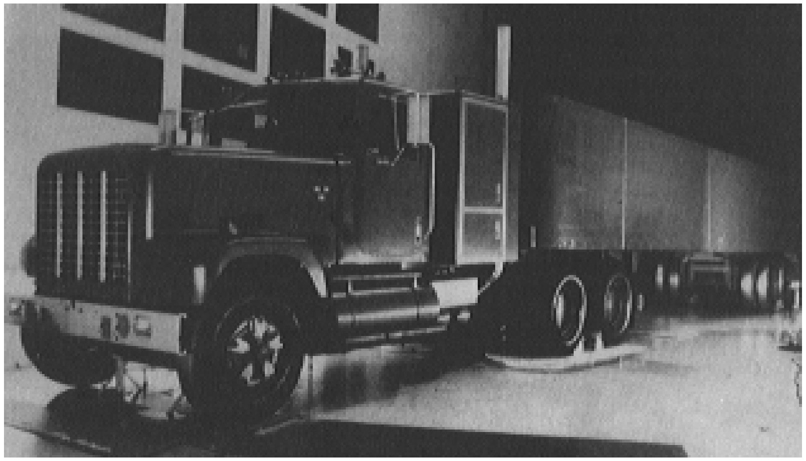
The DOE is interested in improved heavy vehicle thermal management for fuel reduction.

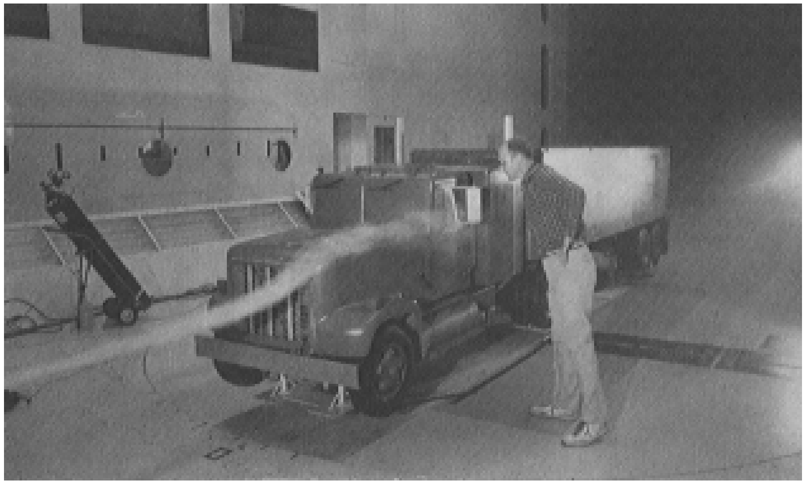
The engine cooling airflow contributes to aerodynamic drag

1970's - 1980's Designs

$\overline{C}_{Dtotal} = 1.0 - 0.85$

engine air cooling is 3.8% of $\overline{C}_{Dtotal}$





Efficient aerodynamic design leads to less splash and spray.

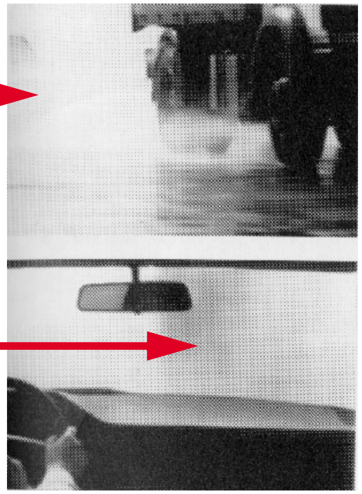
1993 Annual Review of Fluid Mechanics
Photos Courtesy of Mercedes-Benz

Car disappears behind water spray

Standard Mudguard

car not visible

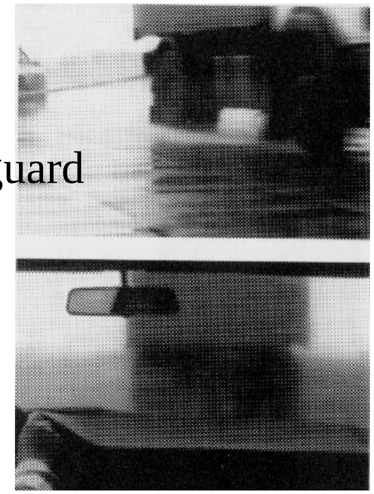
truck not visible
to car driver



Grooved Mudguard

reduced water flow
between tire and mudguard

truck and car can
be seen clearly



Ref. SAE paper 950631

Funding has been less than required.

	Computations & Experiments	Evaluation of Current & New Technologies	Final Report	Total requested/ Year	Total received/ Year
FY98	$276K	$34K		$310K	$325K
FY99	$630K	$5K		$635K	$441K
FY00	$1,045K	$188K		$1,233K	$710K
FY01	$1,095K	$188K		$1,283K	
FY02	$855K	$161K		$1016K	
FY03	$818K	$161K		$979K	
FY04	$120K	$124K	$34K	$278K	
TOTAL				$5,734K	

Funding for FY98, FY99, and FY00

	FY 98	FY 99	FY 00
LLNL	$100K	$170K	$210K
SNL	$100K	$80K+	$135K
USC	$50K	$80K	$100K
Caltech	$50K	$80K	$100K
NASA	$25K	$31K	$165K
Totals	$325K	$441K	$710K

It has been necessary to leverage other funding sources.

SNL	- past data obtained at Texas A&M	Free
	- loan of model to NASA	Free
	- LES/DES R&D	LDRD, Tech Base
	- computational resources and more	ASCI
USC	- instrumentation	Caltrans, NSF
Caltech	- LES model development	ASCI, DOD, internal
	- computational resources	ASCI, NSF, DOD, internal
NASA Ames	- 7’x10’ wind tunnel tests	Free
	- 12’ wind tunnel tests	1/3 Cost
	- loan of Navistar’s model	Free
LLNL	- computational resources	ASCI
	- LES and code development	ASCI/Tech Base, other

Possible funding sources are being investigated.

DOE	Request for Proposals
	Aerodynamic drag (LLNL, SNL, NASA, USC, Caltech)
	Thermal management (ANL)
	Friction and wear (ORNL)
	Rolling resistance (ORNL)
DOD	Request for Proposals
	Parasitic loss reduction
BES	R&D on simple shapes for turbulence model development

We have a full calendar.

Progress Report (4/00)

DOE/EE/BES Proposal (4/00) - Assistance from OHVT needed

DOE RFP

- Establish scope and industrial partners (WITHOUT TRAVEL)
- Pre application (before 5/1/00)
- Final proposal (before 5/15/00)

DOD RFP

- Establish scope and partners - must be complimentary to DOE proposal
- White paper (2/29/00)
- Final proposal (before 4/28/00)

SAE Meeting, Washington, DC (6/00)

- Abstract submitted
- Draft paper (3/15/00)
- Final paper and presentation

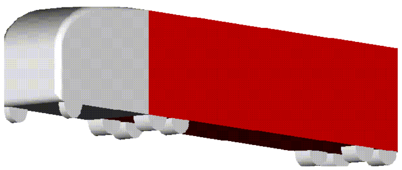
Working Group Meeting (7/00? Travel?)

Progress Report (7/00)

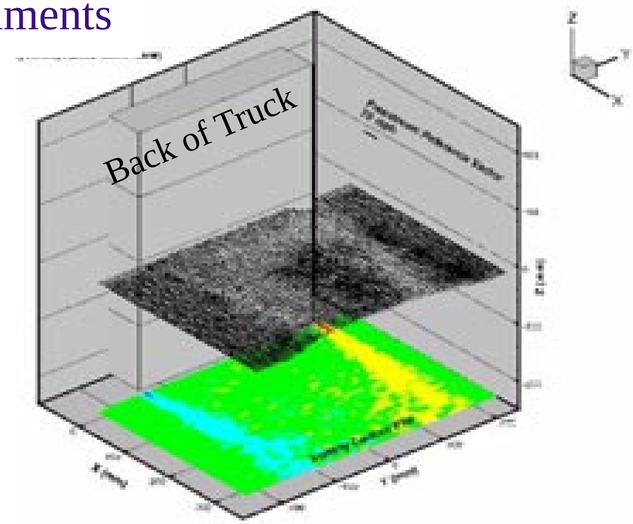
Accomplishments: The team of experts is established and significant progress has been made.

- Established multi-lab, multi-university team
- Working relation with industry
- Multi-year program plan in place
- Experiments completed for baseline case (first time 3D, unsteady velocity field measured in a production wind tunnel)
- Understanding of gap flow phenomena
- Preliminary RANS and LES calculations
- Advanced model development in progress
- Continued data base development
- Preliminary design effort

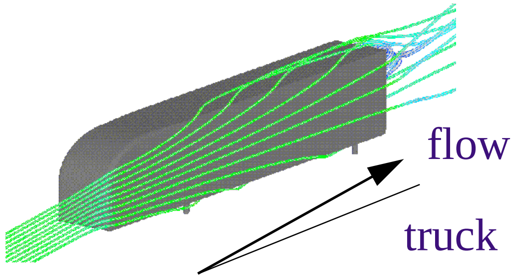
Baseline Case



Experiments



Computations



Options for FY'00 Experiments at NASA ARC

Two Possibilities and Associated Issues

- 12' Pressure Wind Tunnel
  - Cost and schedule
- 7x10 Wind Tunnel
  - Technical payoff

12' Experiment Objectives

- Re effect on wind-averaged drag
  - Range from 0.5 to 5 million (based on width)
- Re effect on drag components - mirrors, bars, gap/side extenders, base-drag-reduction devices, etc.
- CFD validation data
  - Skin friction
  - Pressure distributions (PSP works great at high pressure)
  - Unsteady pressures
  - PIV <u>not</u> possible this year

Model for 12' Experiment
Provided by Navistar

- Navistar routinely tests to ~140 mph (50 psf) (at 60 mph, dynamic pressure is 9 psf)
- Full-scale Re obtained in 12' at 6 atm (80 mph or q of 96 psf)
- Most model parts meet safety factor of 4 - those that don't can be replaced
- Balance arrangement like that used for America's Cup keel or fabricate new single- or two-axis balance (not an expensive proposition)
  - » Max drag <400#
  - » Max side force < drag
- Yaw range of ±14° for wind averaging
- Generic model with CAD definition

12' Issues

- 3-week slot open in August - too soon to do the job right
- Cost is $160K/week plus power
  - Power ~$10K/week
- PIV not possible in this time frame
- Funding won't be available in time

Cost Breakdown for 12' Experiment

What it takes to do the job right

Item	Explanation	Cost basis	Per	Amount	Item cost
Direct Labor	Contracted labor research engineer	$10,000	FTE month	8.0	$80,000
Program Support	Head tax for Experimental Physics personnel	$40,000	FTE year	1.5	$60,000
Wind Tunnel Time	12' PWT charges	$160,000	week	3.0	$480,000
Power Cost	Cost of power to run wind tunnel	$10,000	week	3.0	$30,000
Model Mods	Strengthen parts, balance mods	$15,000	each	1.0	$15,000
Instrumentation:					
	PIV insertion optics	$30,000	each	1.0	$30,000
	Laser installation	$15,000	each	1.0	$15,000
	Camera housings	$10,000	each	2.0	$20,000
	Second laser for fwd scatter	$40,000	each	1.0	$40,000
	Seeder installation	$25,000	each	1.0	$25,000
	PSP	$12,000	each	1.0	$12,000
				Instr. Total	$142,000
Center taxes	Directorate, Division, & Branch taxes	3%	of net	$880,000	$26,400
"Handling fee"	Tax on reimbursable $	6%	of net	$880,000	$52,800
				Total	**$886,200**

Total for 2 week test $716,200

Options for 7x10 Experiments

- Full truck geometry from Navistar
  - CFD validation data on full truck configuration
    - » Probably without ugly details
  - Additional base-drag reduction device demonstration
- ***Modified GTS model*** (Preferred option)
  - Include gap/side extenders for higher-Re CFD validation
  - Additional base-drag reduction device demonstration
- With either option, provide opportunity for tests of USC model at lower blockage and higher Re

Proposed Mods to GTS Model

Side view

Cut gap in model sized appropriately
for long-haul trucks

Instrument gap and side extenders to measure mean and fluctuating pressure

Top view

Side extenders to model cavity on trucks
- transparent set to allow PIV measurements
- instrumented set for mean and unsteady pressure

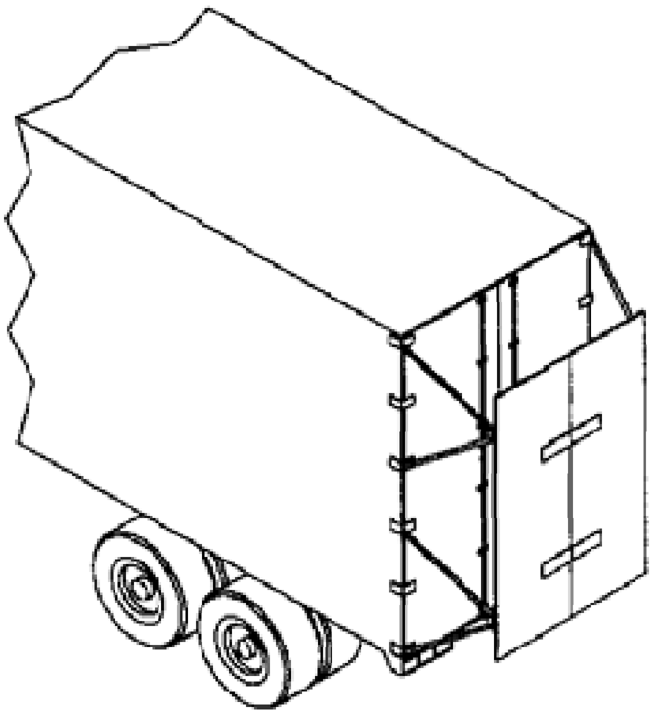
Fabricate set of plates to allow restoring model to GTS configuration

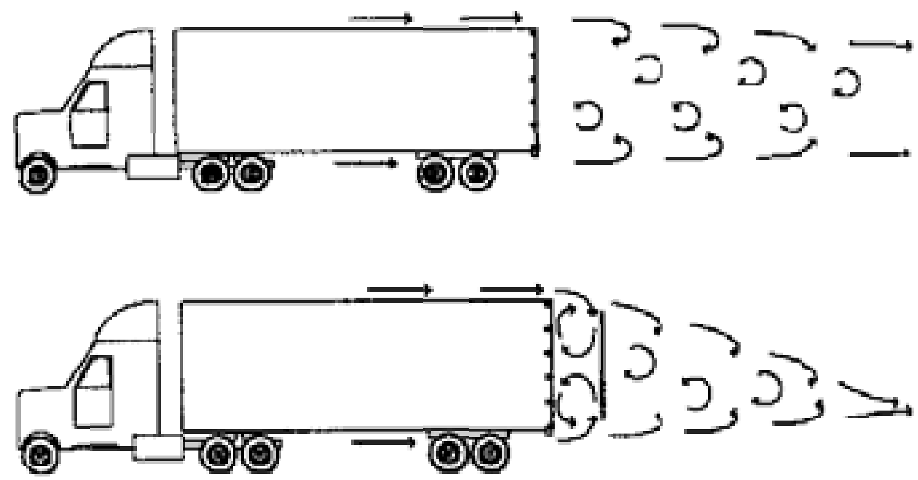
Ames Research Center

Experimental Physics Branch

Aeroplate™ Concept

- Developed by B.L.A. Technologies

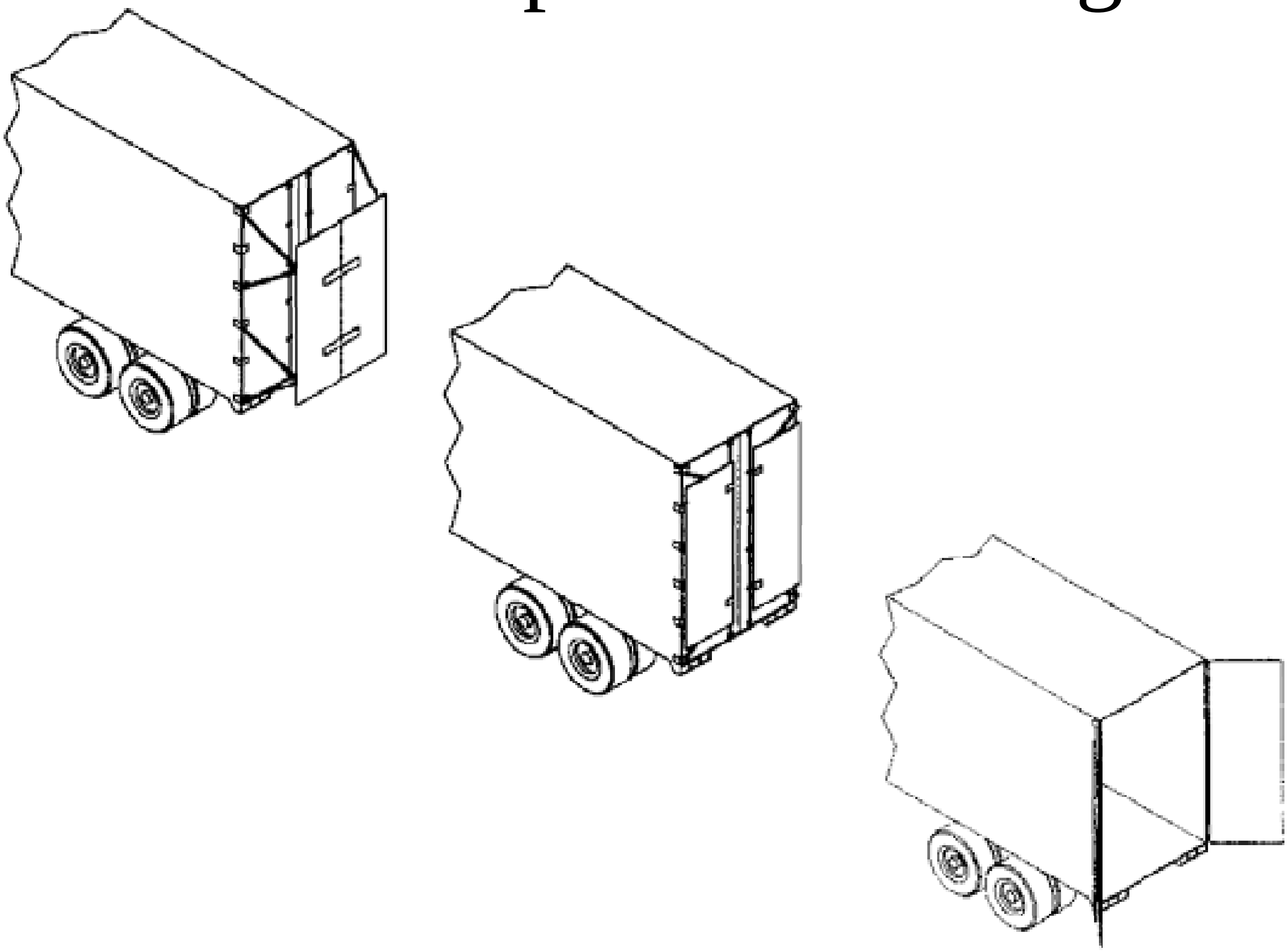




Ames Research Center

Experimental Physics Branch

Aeroplate™ Folding



Ames Research Center
Experimental Physics Branch

Proposed Test Matrix

- Side extender variations for drag (3 or 4)
- Select 2 extenders for PIV and other detailed measurements
  - At least 2 yaw angles
- Repeat drag data for baseline GTS
- Examine drag reduction with and without gap for
  - CDI boat-tail plates
  - BLA drag plate
  - Other drag-reduction devices?
- If noticeable difference in drag reduction with gap, perform PIV measurements in wake to diagnose

Measurements

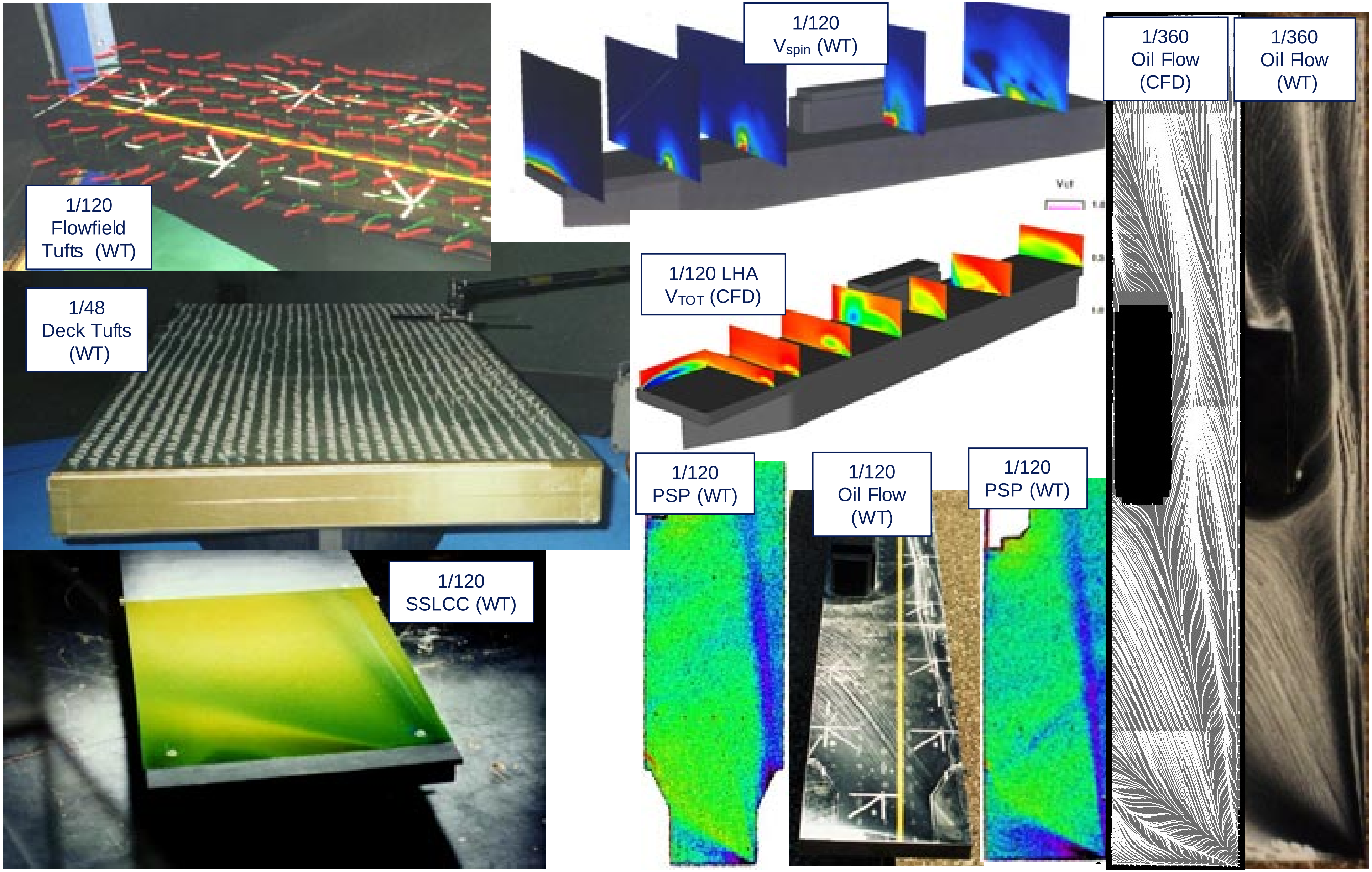
- Pressure distributions (no PSP unless big demand)
- Oil film skin friction (limited configurations)
- 3-D PIV in gap (and possibly in wake)
- Mean and unsteady pressures in gap area and rear door
- Need to define measurement requirements for USC model

Proposed CFD Work at Ames

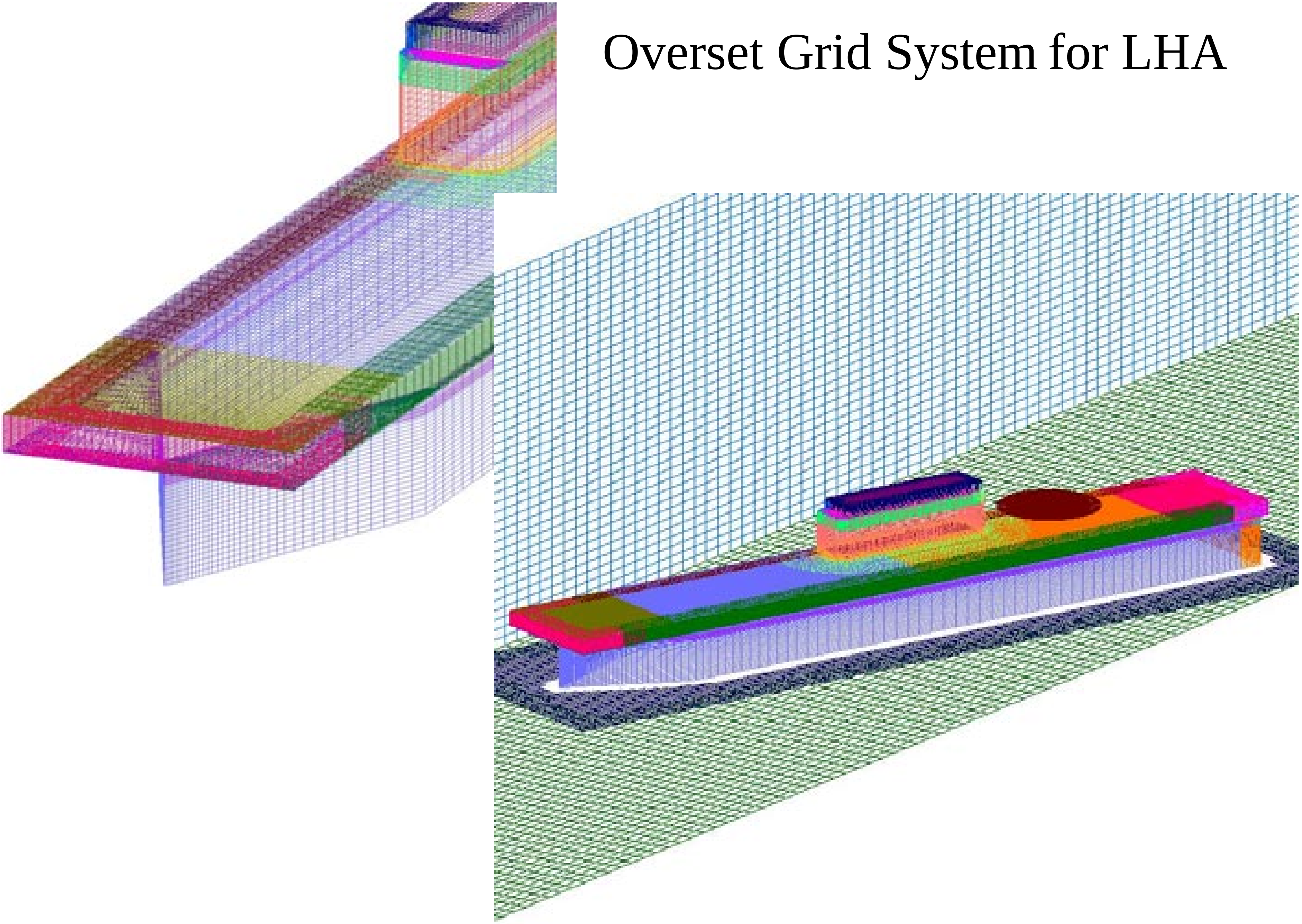
- Overflow computations of geometry with gap & side extenders at 2 yaw angles and 2 Re
- ~2 month effort
- Donovan Mathias will do work - running ship air wake computations for Navy
- Similar to Navy Ship Airwake computations currently underway

Sample Effort #1:
LHA/LHD Vortex Visualization

(All cases 340 deg WOD; vortex core located near port deck edge)

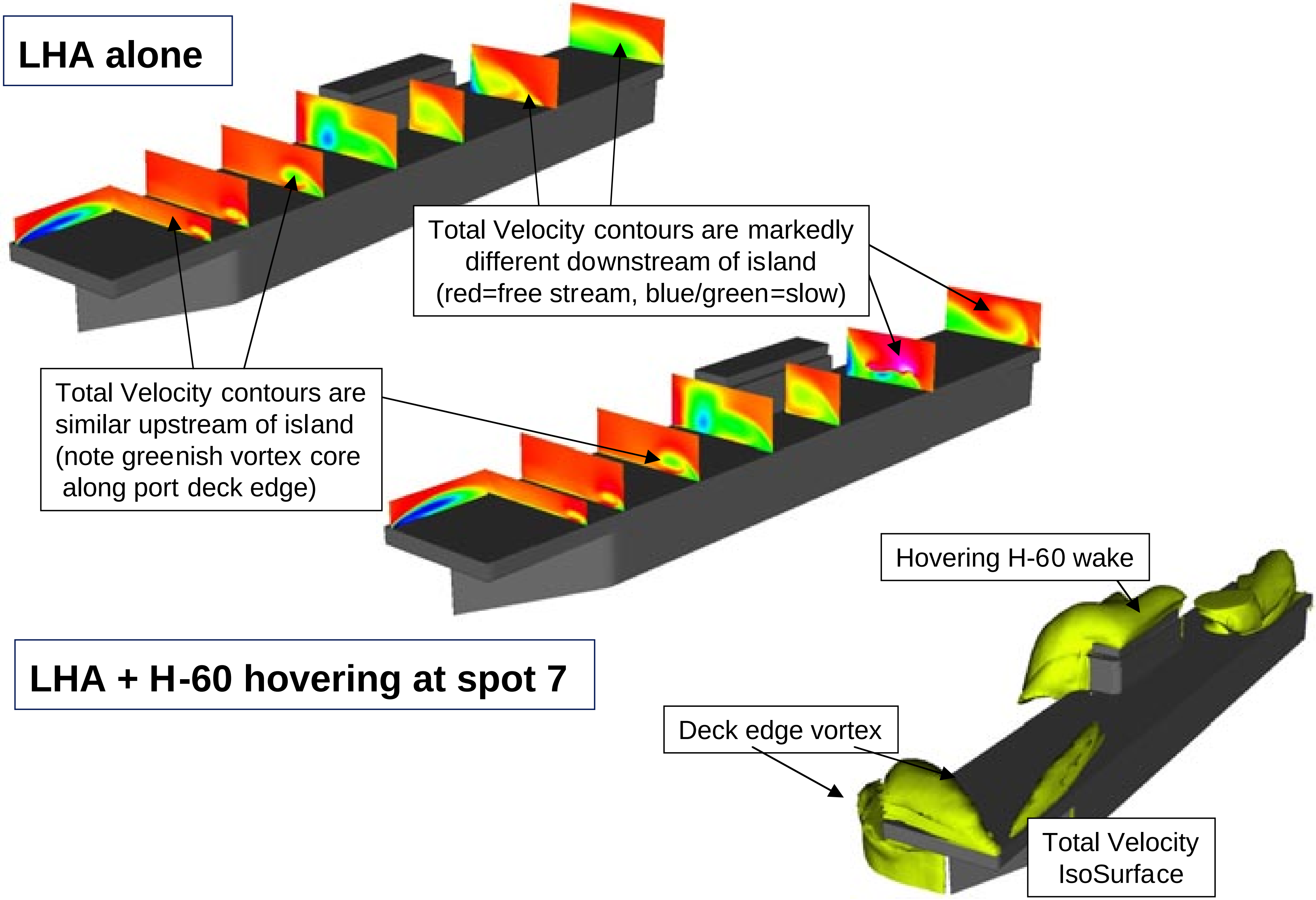


Overset Grid System for LHA



Effect of Hovering H-60 Rotor Thrust on Future LHA[1] Flow Patterns

(Structured RANS CFD Solutions by D. Mathias, 340 deg winds)



Ames Activities for FY '01

- No real need for additional testing at low Re
- Experimental work at Ames should be high-Re only
  - Maybe not plan any experiments for next year unless 12' experiment can be funded
- Overset grid computations?

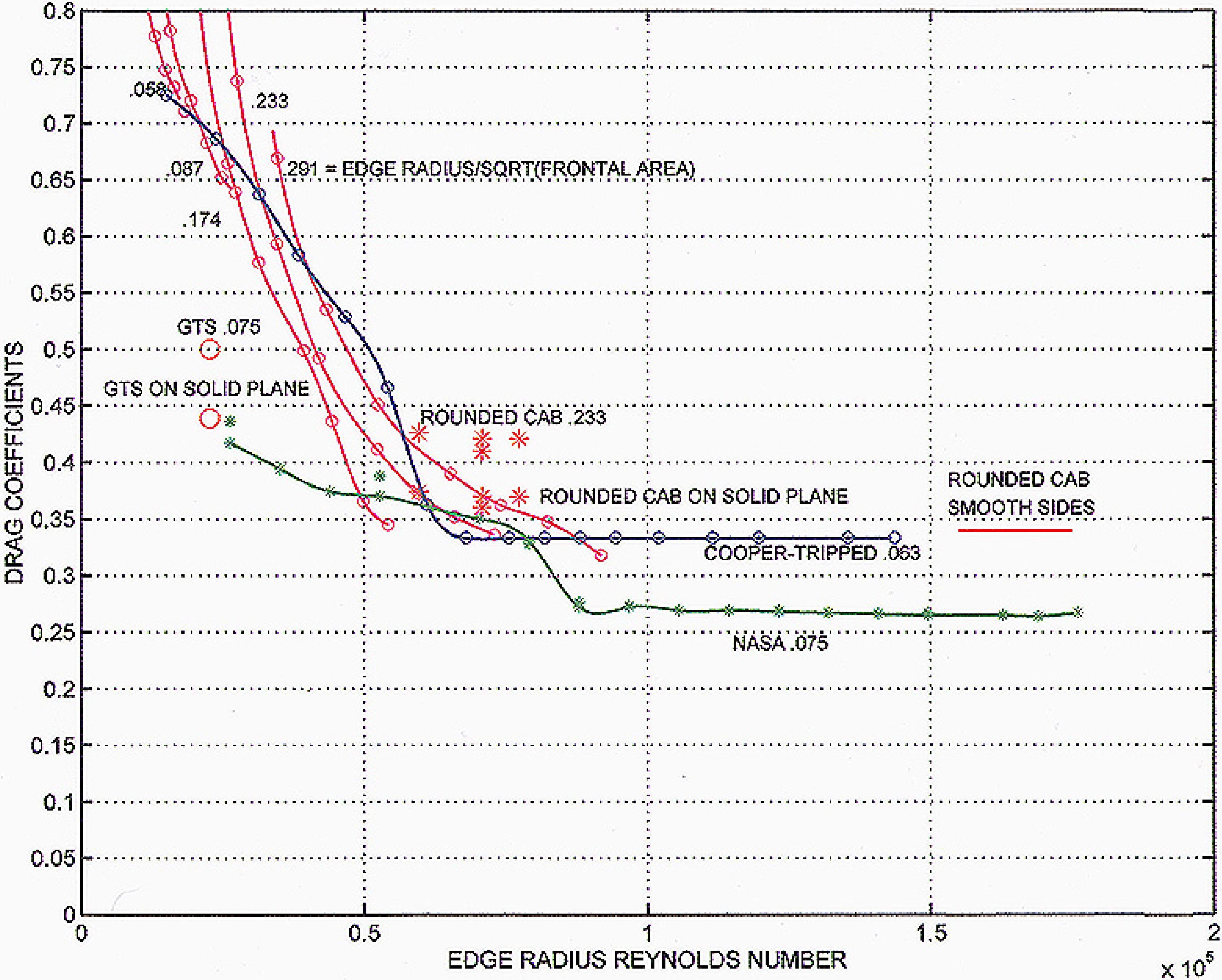
USC Results/Plans

Fred Browand/Mustapha Hammache

Resolving Differences in Measured Drag Coefficients

Tractor-Trailer Gap Flow at Yaw

Modification of Trailer-Base Flow by Means of Oscillatory Perturbations


DRAG COEFFICIENTS
EDGE RADIUS REYNOLDS NUMBER
x 10^5
.058
.233
.087
.291 = EDGE RADIUS/SQRT(FRONTAL AREA)
.174
GTS .075
GTS ON SOLID PLANE
ROUNDED CAB .233
ROUNDED CAB ON SOLID PLANE
ROUNDED CAB
SMOOTH SIDES
COOPER-TRIPPED .063
NASA .075
0.8
0.75
0.7
0.65
0.6
0.55
0.5
0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
0
0.5
1
1.5
2

Computational Prediction for a Simplified Truck Geometry

Kambiz Salari

Walter H. Rutledge

Aerosciences and Compressible Fluid Mechanics Department

Sandia National Laboratories

Heavy Vehicle Aerodynamic Drag: Working Group Meeting

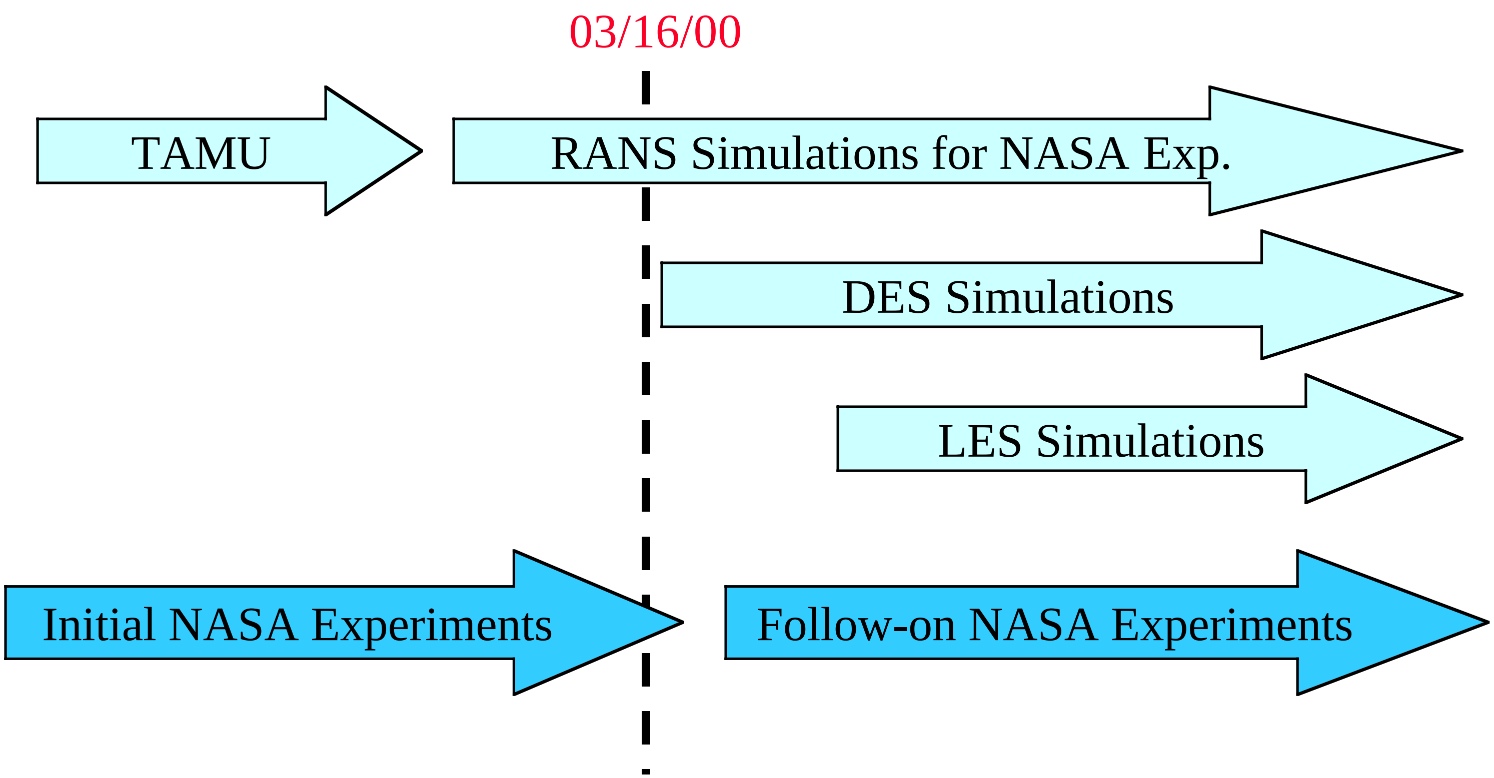
Lawrence Livermore National Laboratory

March 16, 2000

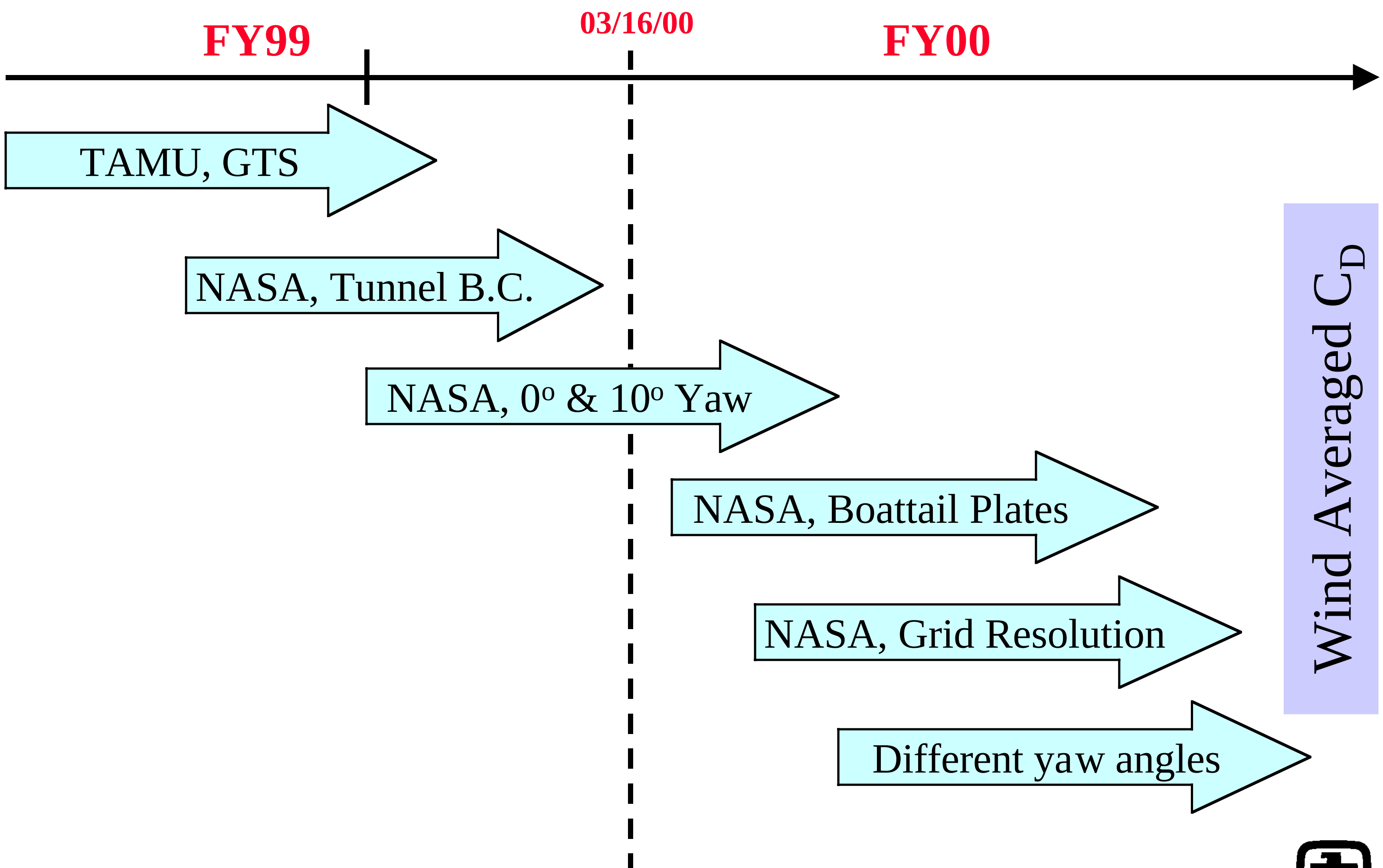
Outline

- Sandia computational approach
- Ongoing Sandia simulations
- Leveraging from other programs
- Modeling wind tunnel experiment
- Tunnel empty flow simulation
- Flow quality in the tunnel test section
- Results for 0° and 10° yaw
- Conclusions

Sandia Computational Approach



Ongoing Sandia Simulations



Leveraging from Other R&D Programs

- DOE Accelerated Strategic Computing Initiative (ASCI) Aerodynamics program
  - RANS Code Development (SACCARA)
  - Intel Teraflop access time
  - Verification & Validation Activities
- Sandia Engineering Sciences Research Foundation (Tech Base, LDRD)
  - Transition and Turbulence Modeling
  - DES Research
- Potential Industrial CRADA
  - LES Development & Application

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The Six Recommended Practices of a "Validation Experiment"

- Validation experiment should be jointly designed and executed by experimentalists and code developers
- Validation experiments should be designed to capture the relevant physics, all initial and boundary conditions and auxiliary data (viscosity, flow rates, etc.)
- Validation experiments should utilize any inherent synergisms between experiments and computational approaches (try to offset strengths and weaknesses between the two)

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The Six Recommended Practices of a "Validation Experiment" (cont'd)

- **The flavor of a blind comparison of computational results with experimental data should be a *goal* (that is, it should be an attempted to be a true prediction not a code calibration)**
- **Level of complexity of physics should be attacked in a *series* of validation experiments (start off simple with experiments at high confidence and work up to more complex flows, e.g., turbulent flows)**

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The Six Recommended Practices of a "Validation Experiment" (cont'd)

- **Develop and employ experimental uncertainty analysis procedures to delineate and quantify systematic and random sources of errors**

Reference: Oberkampf and Aeschliman, AIAA Journal, May 1998, pp. 733-741.

Reference: AIAA Guide to Verification and Validation of Computational Fluid Dynamics

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Modeling Wind Tunnel Experiment

Computational Boundary Conditions

- **Inflow**
  - Boundary layer profile
  - Uniformity of the incoming flow
  - Description of turbulent fluctuations (intensities)
- **Outflow**
- **Modeling tunnel walls (blockage)**

NASA 7'x10' Tunnel, Flow Simulation

Test Condition for run 7:

Total pressure = 102,652.76 (N/m^2)

Static pressure = 97,612.51 (N/m^2)*

Dynamic pressure (Q) = 5,040.24 (N/m^2)

Static Temperature = 5° C

Mach number = 0.27

Yaw angle = 0° and 10°

Re = $2x10^6$ (based on truck width)

***Based on equivalent "Tunnel Empty" Condition**

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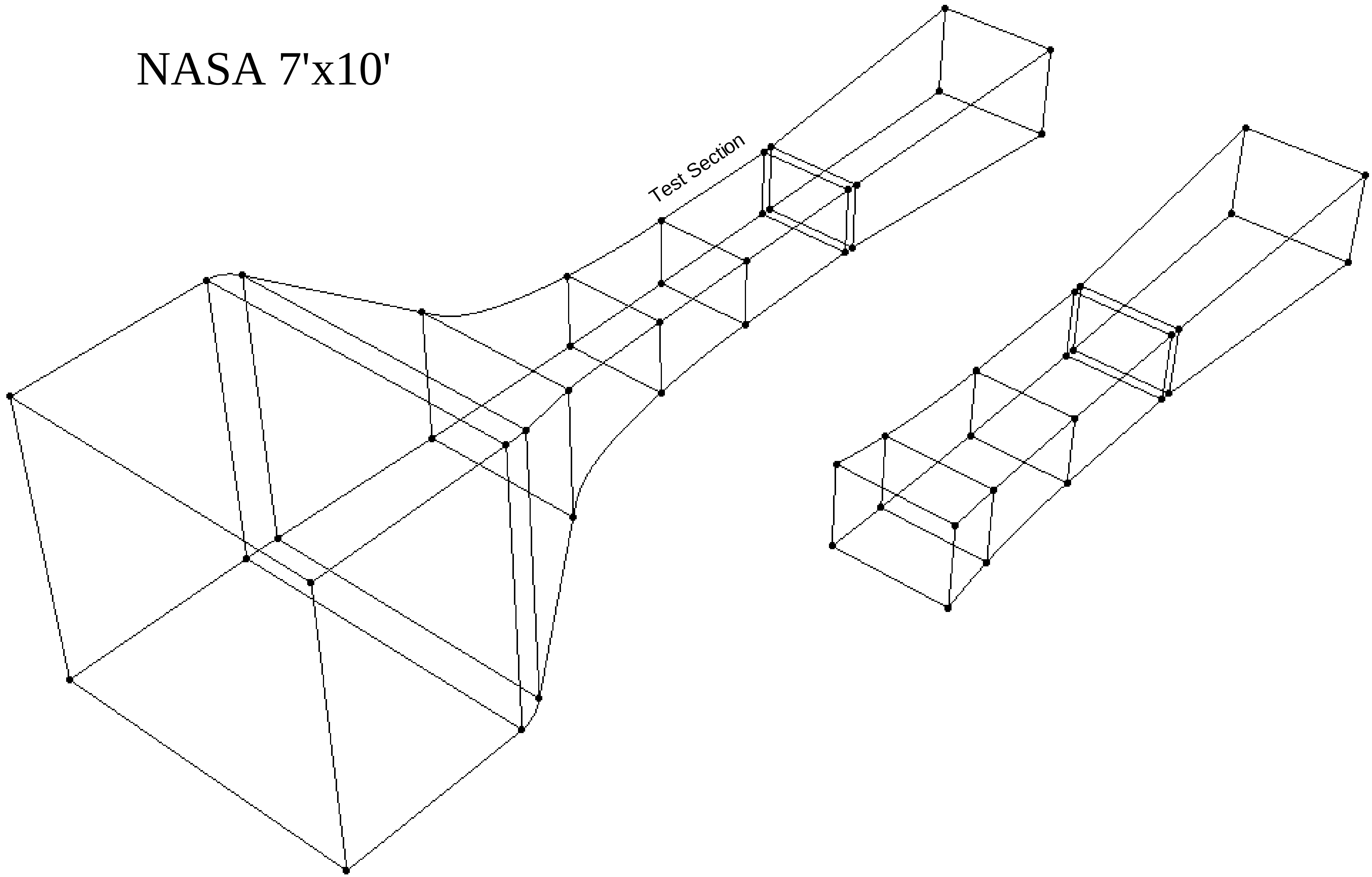
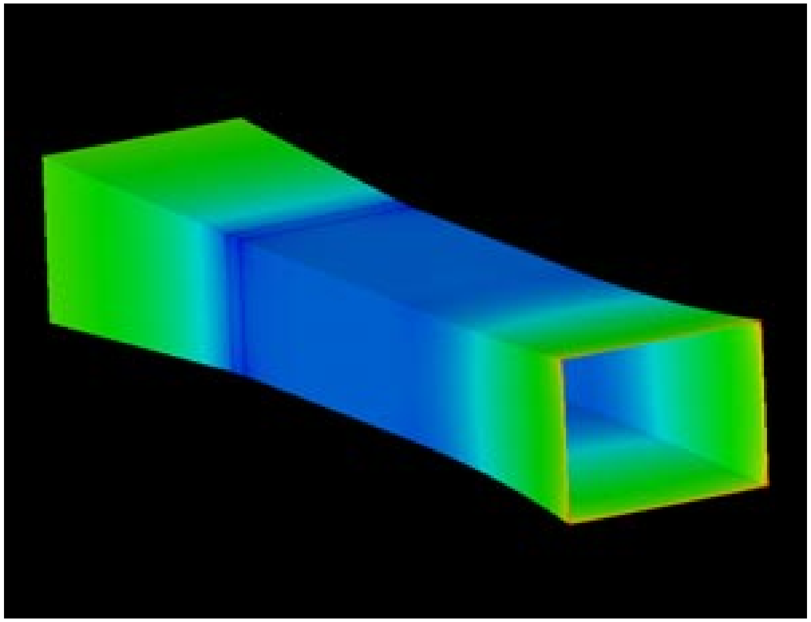
NASA 7'x10'

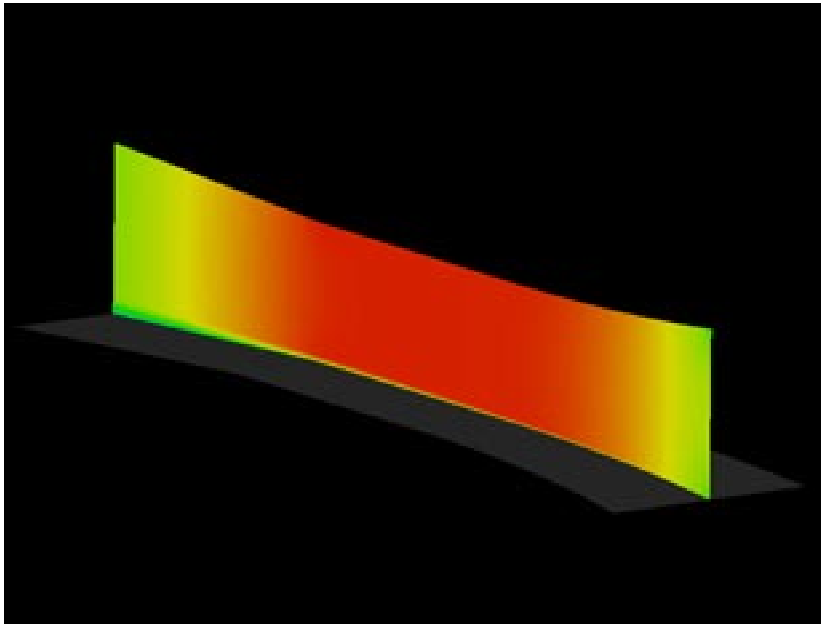


NASA 7'x10' Tunnel, Flow Simulation

Pressure contours



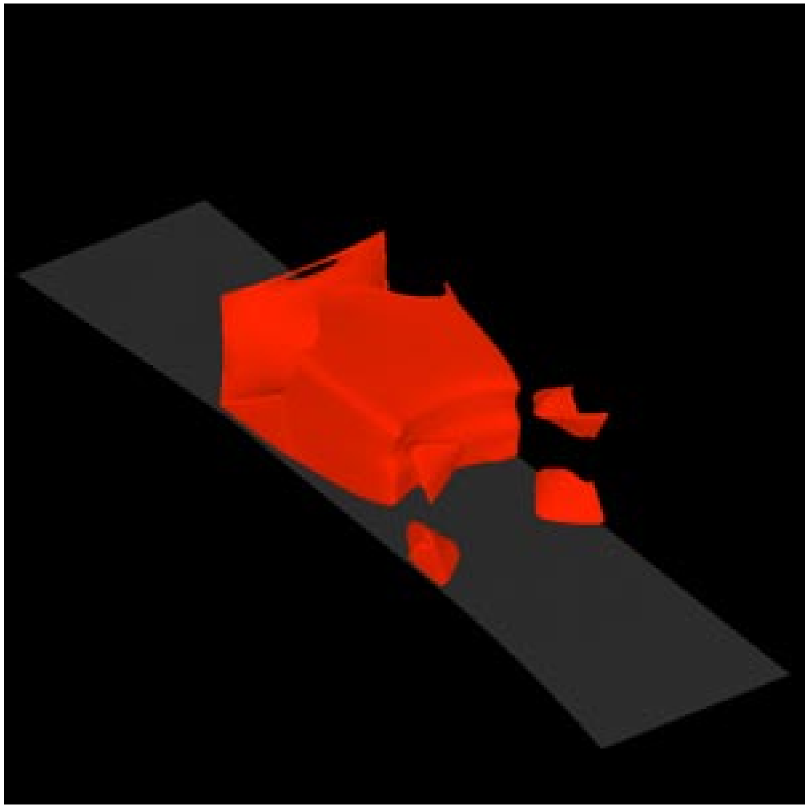
Mach contours (centerline)



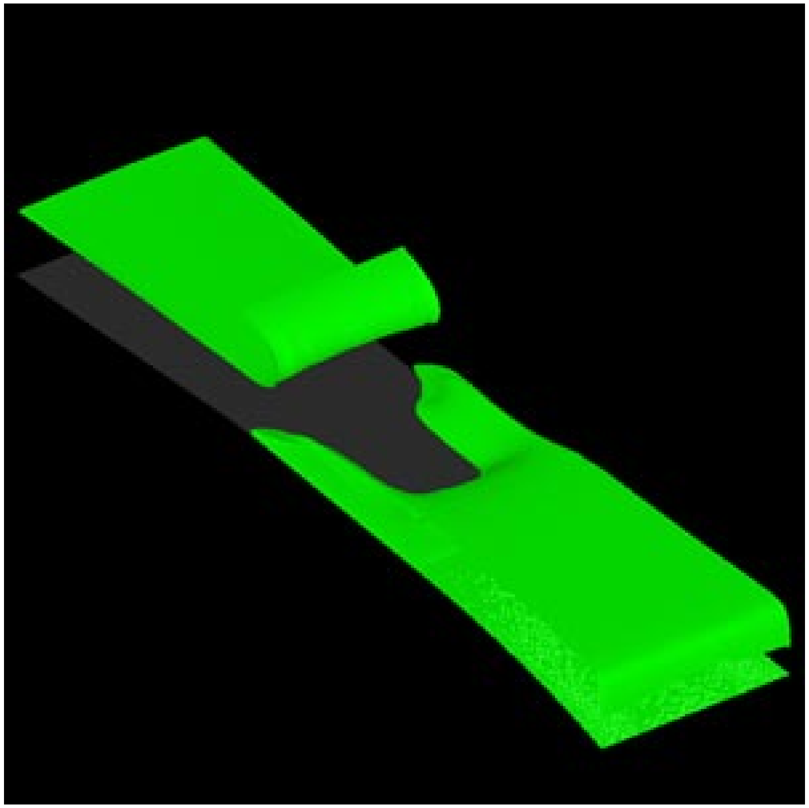
NASA 7′x10′ Tunnel, Flow Simulation, ...

Iso-Surface Plots

u-component, u = 89.92 m/s



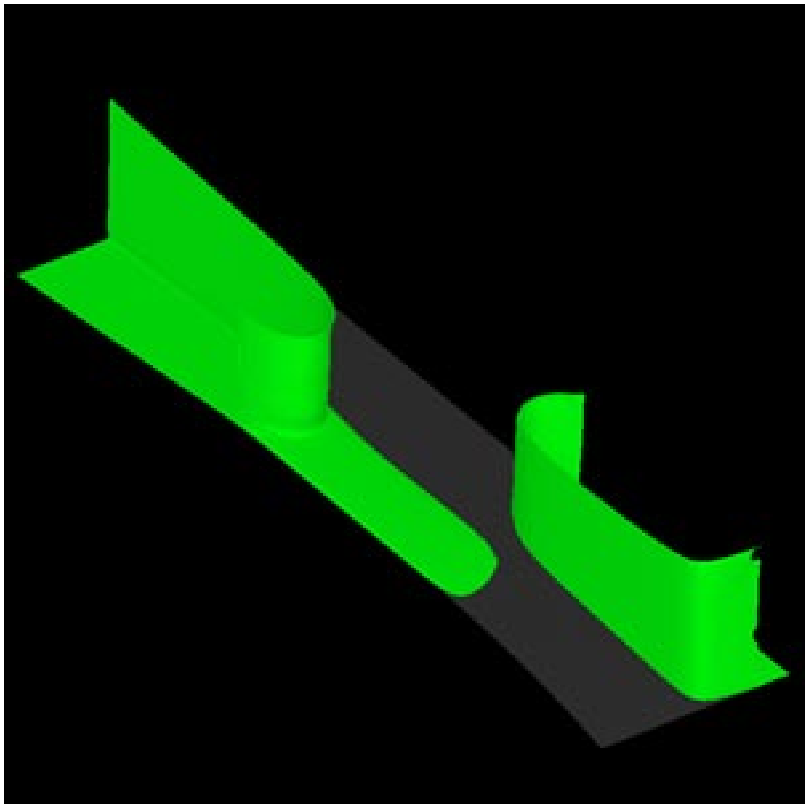
v-component, v = 0.1 m/s



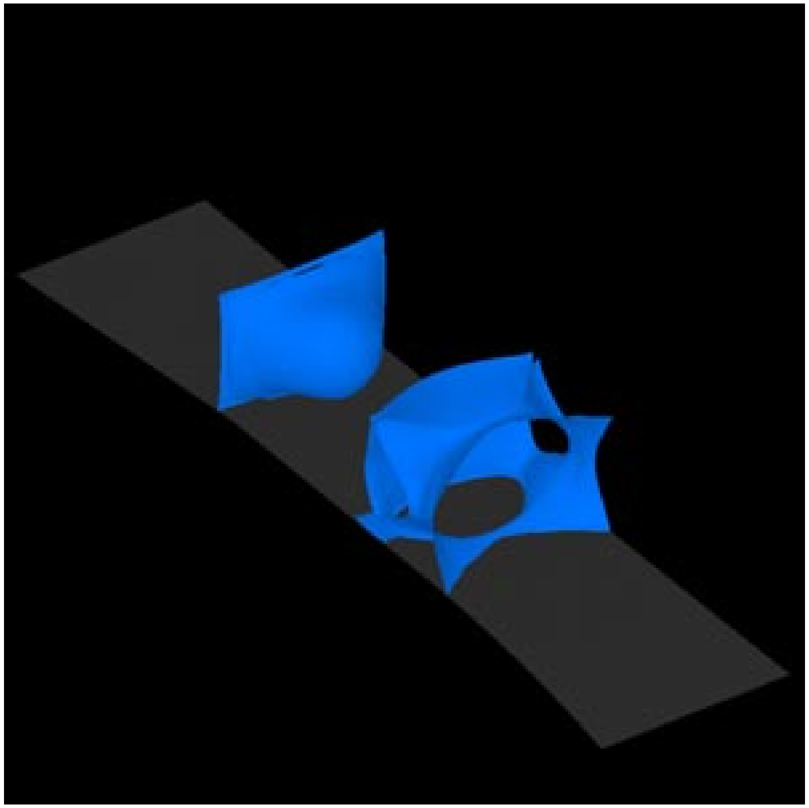
NASA 7′x10′ Tunnel, Flow Simulation, ...

Iso-Surface Plots

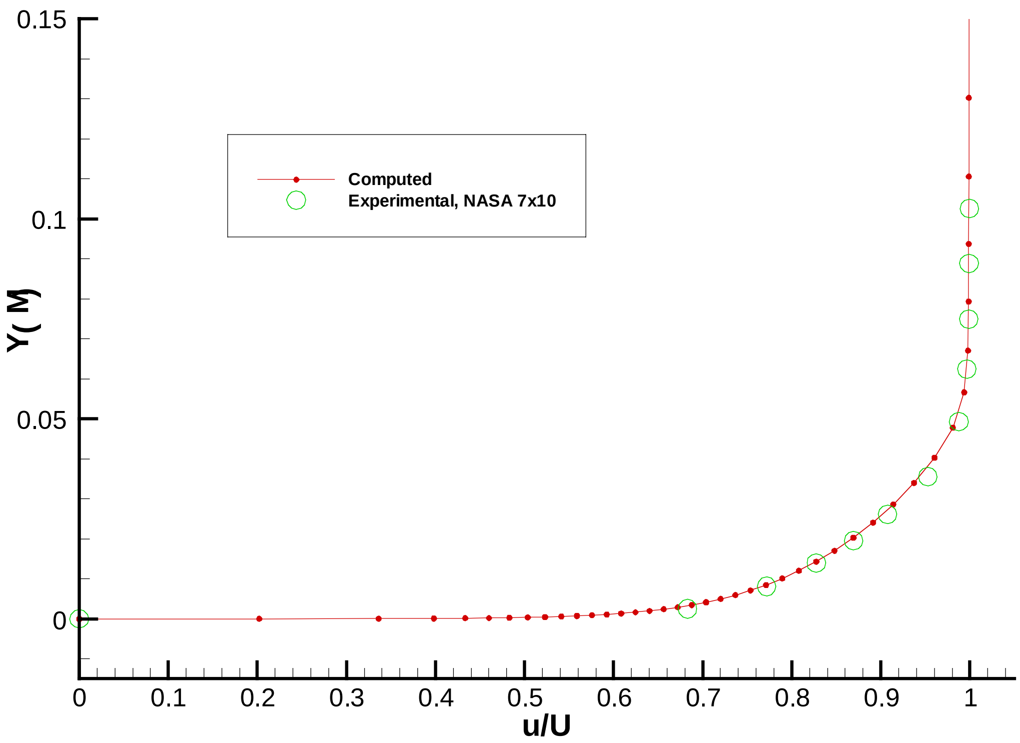
w-component, w = -0.01 m/s



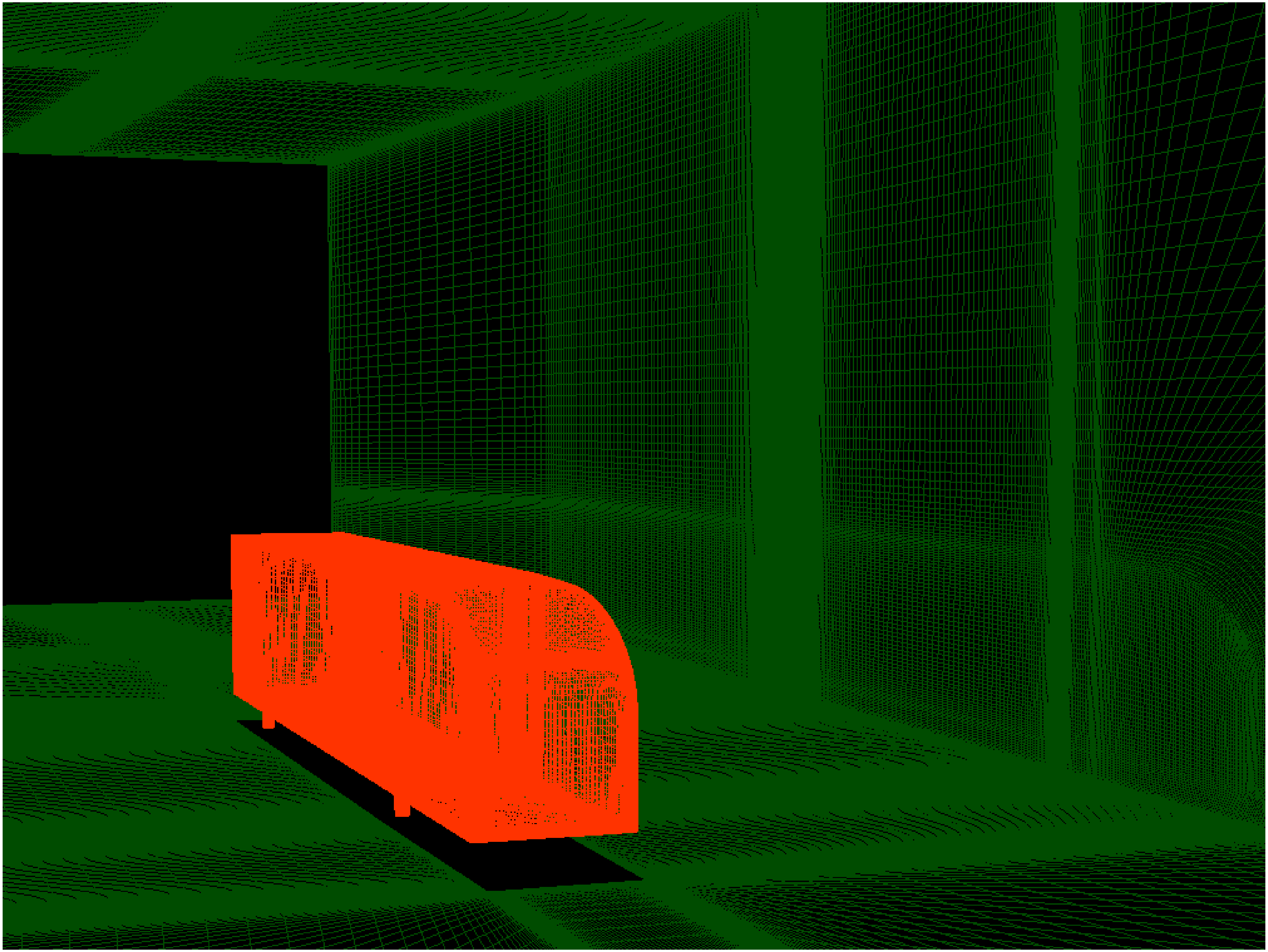
Pressure, P = 97613 Pa

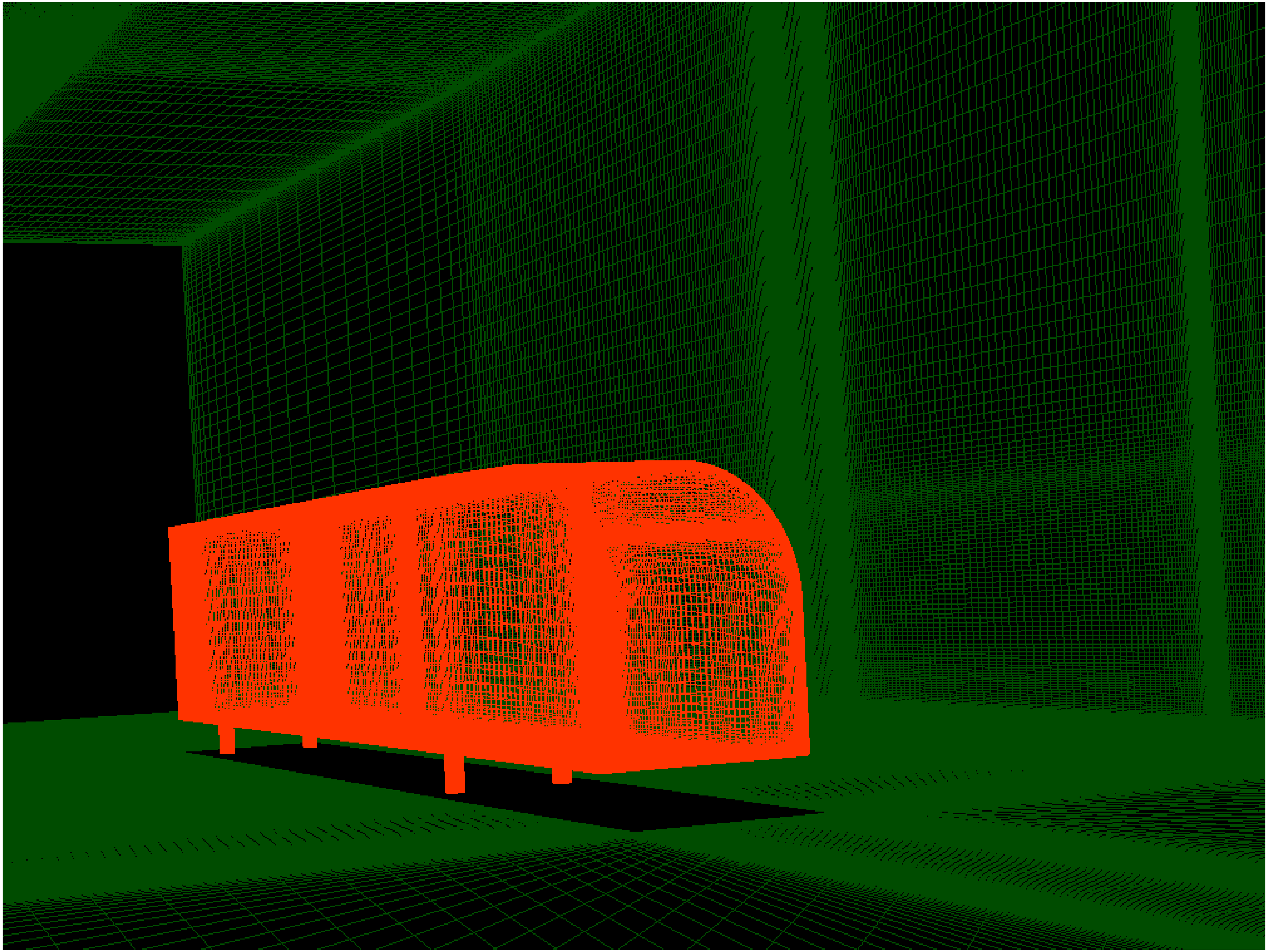


Inflow Velocity Profile (Test Section)



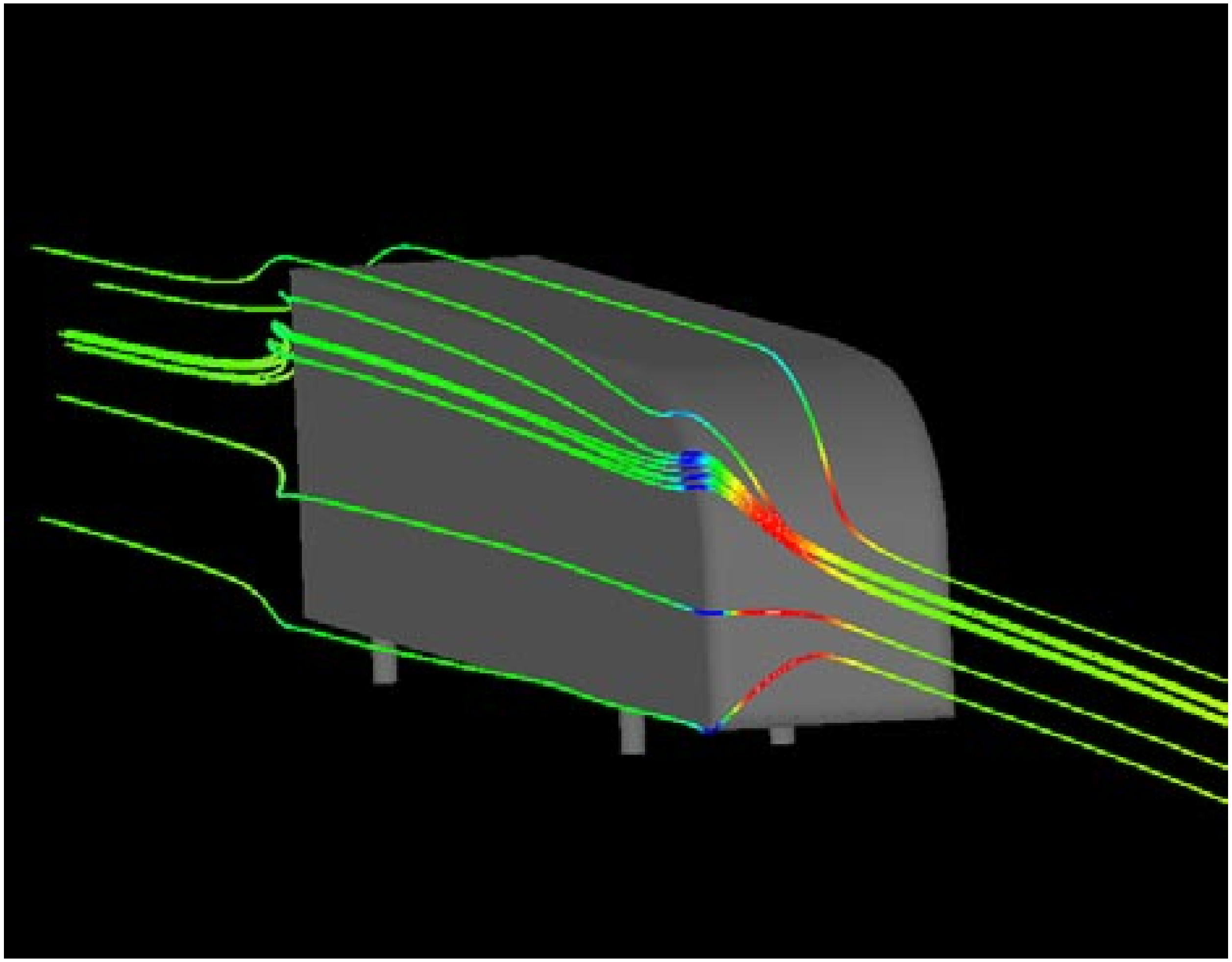

USC
CALTECH





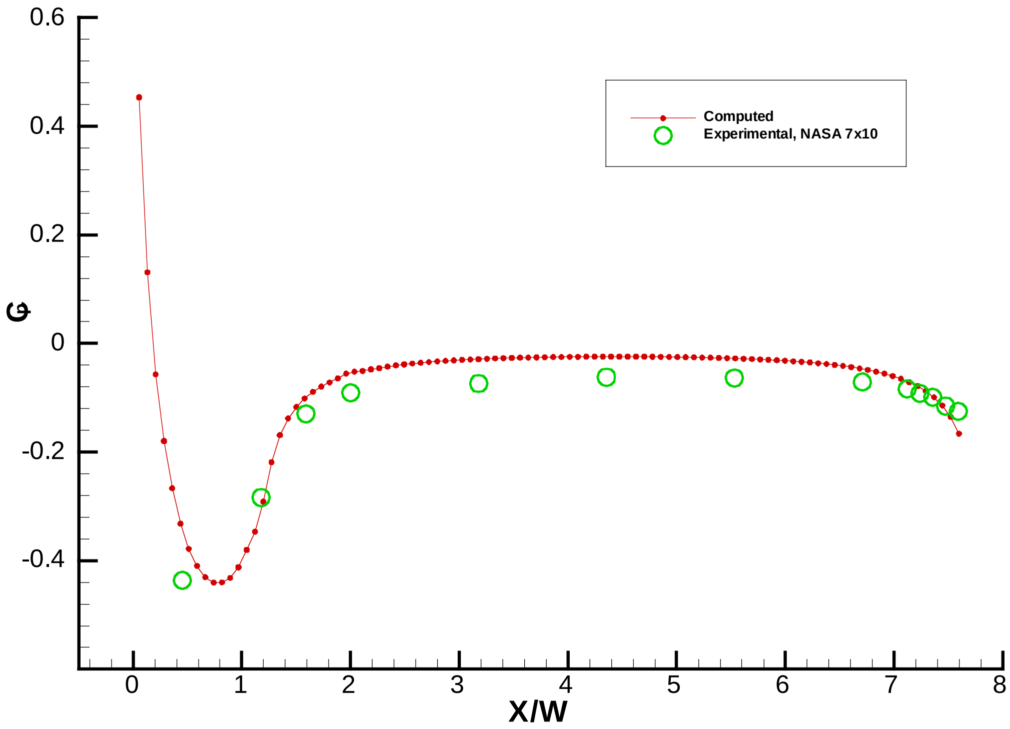
Particle Traces, 0° yaw

Particle traces are colored by pressure magnitude



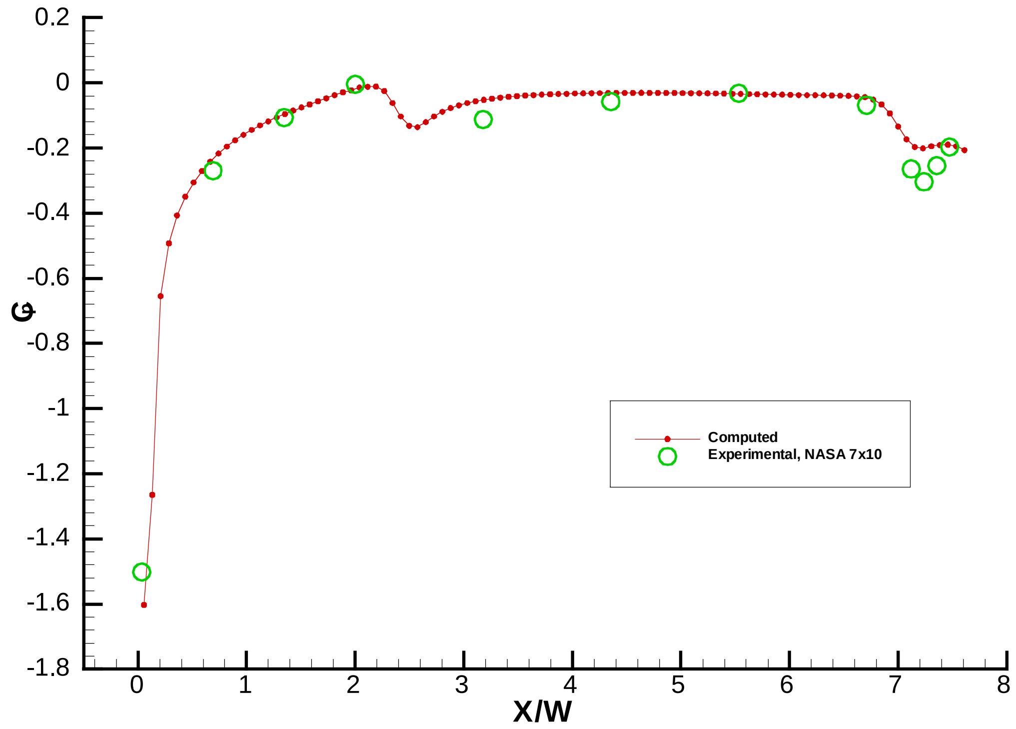
Surface Pressure Coefficient (C_p) Comparison to NASA Data

Y = 1.39 (top of the truck), Z = 0.0 (centerline)



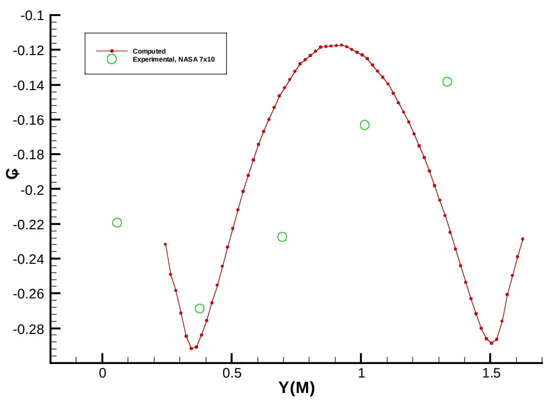
Surface Pressure Coefficient (C_p) Comparison to NASA Data

Y = 0.0 (bottom of the truck), Z = 0.0 (centerline)

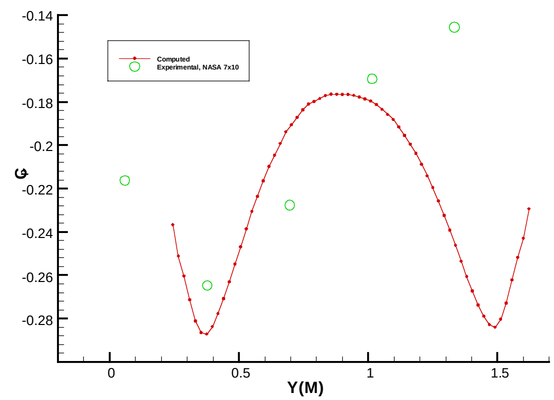


Surface Pressure Coefficient (C_p) Comparison to NASA Data

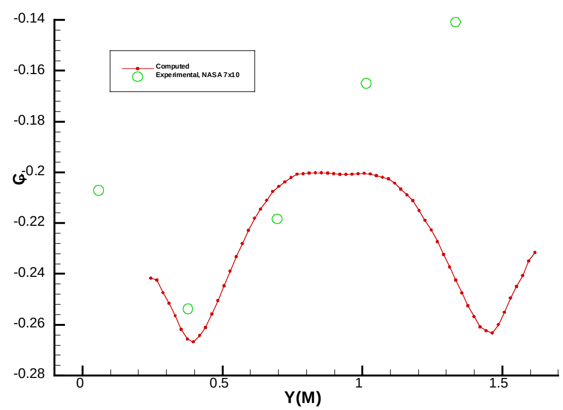
Z = 0.0



Z = 0.22



Z = 0.44



X = 7.59 (back of the truck)
Z = 0.0 (centerline)

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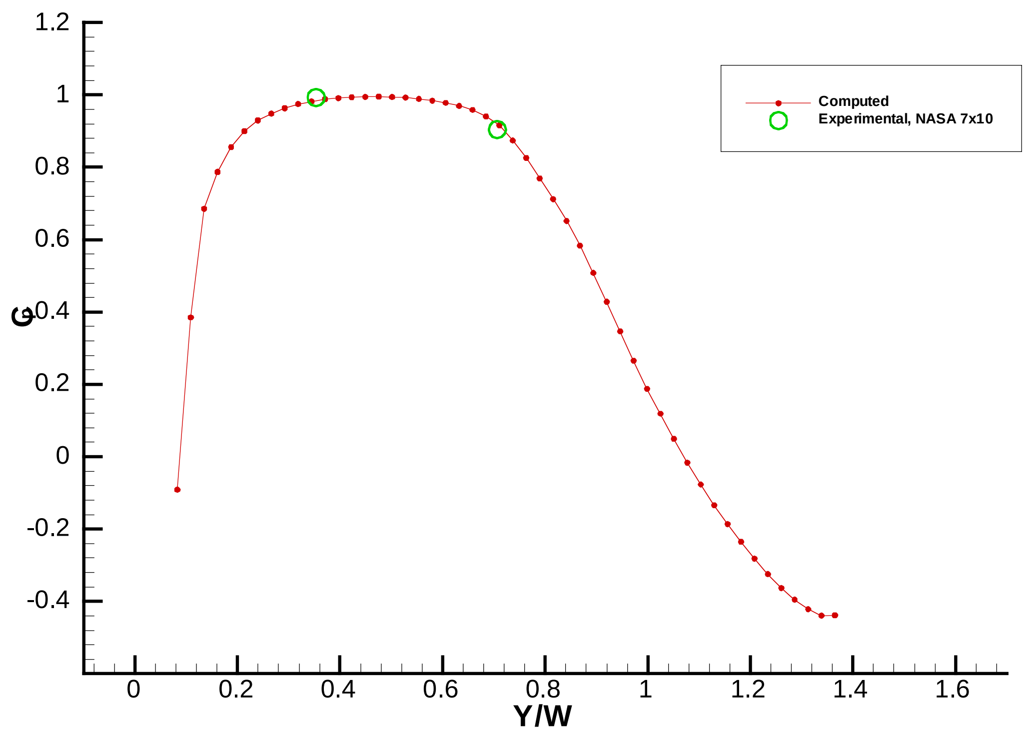
Surface Pressure Coefficient (C_p) Comparison to NASA Data

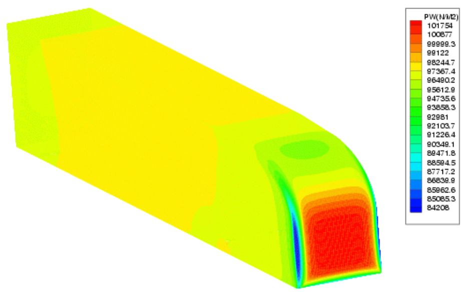
X = 0.0 (front of the truck), Z = 0.0 (centerline)

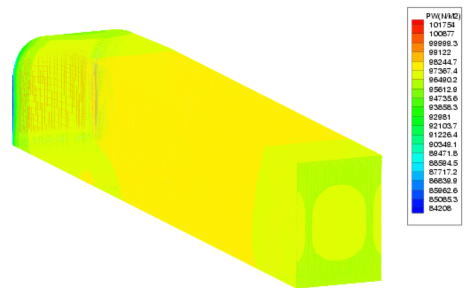


Pressure Distribution on the Surface

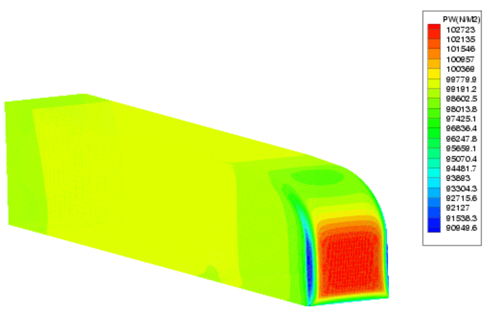
0° yaw

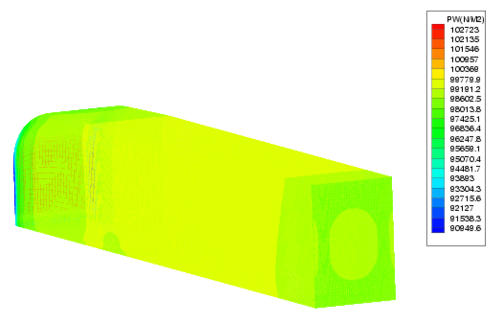
NASA





TAMU





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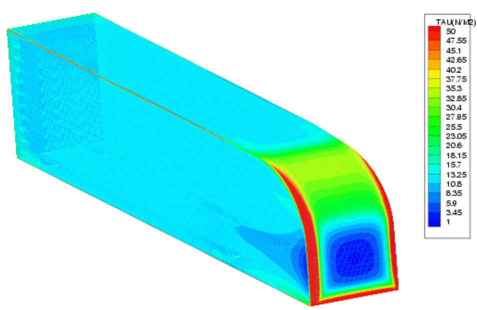
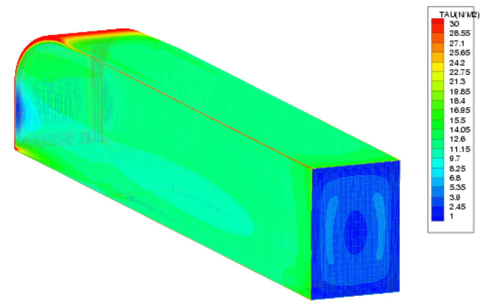
Shear Stress Distribution on the Surface

0° yaw

NASA





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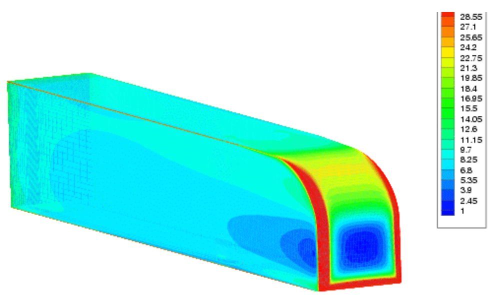
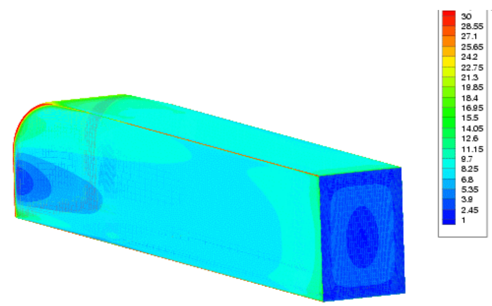
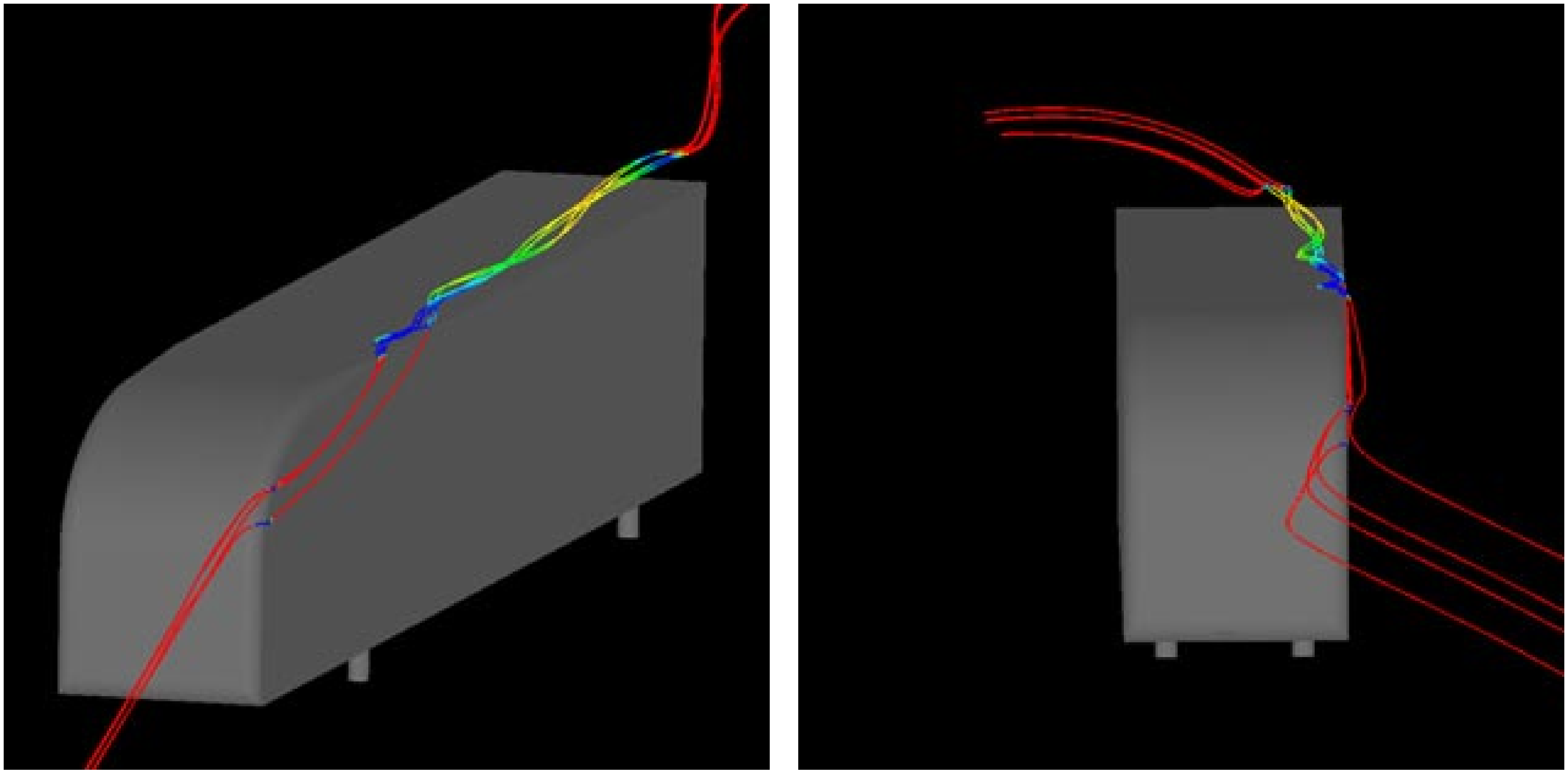




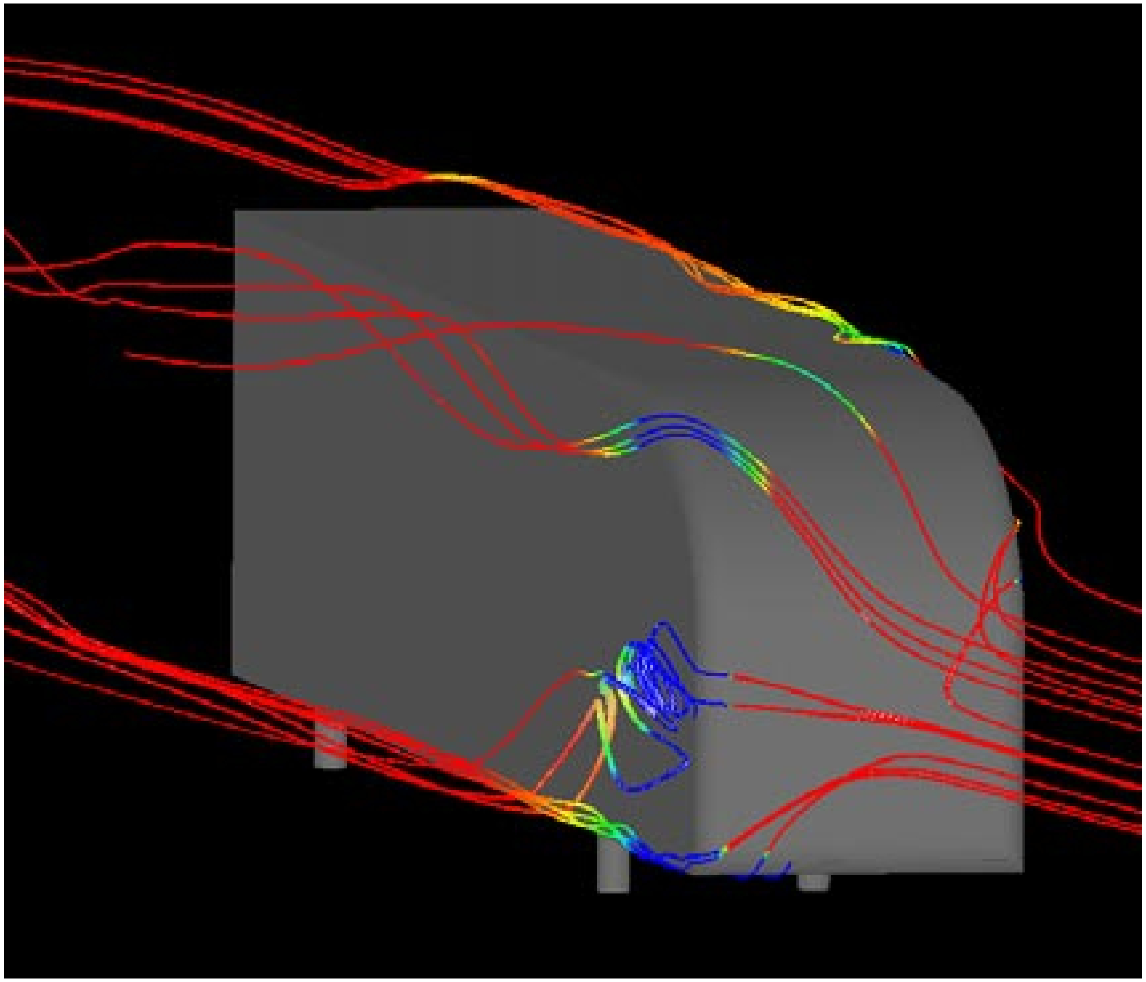
Particle Traces, 10° yaw

Particle traces are colored by pressure magnitude



Particle Traces, 10° yaw

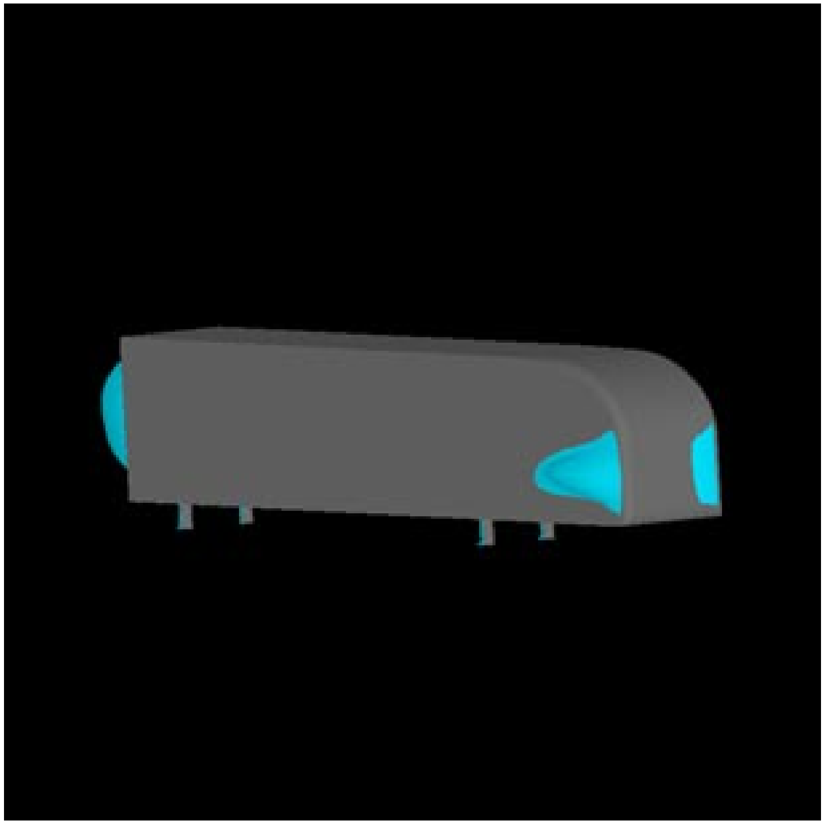
Particle traces are colored by pressure magnitude



Separation Bubble, Leeward Side, 10° yaw

Iso-Surface u = -0.001 (m/s)

NASA



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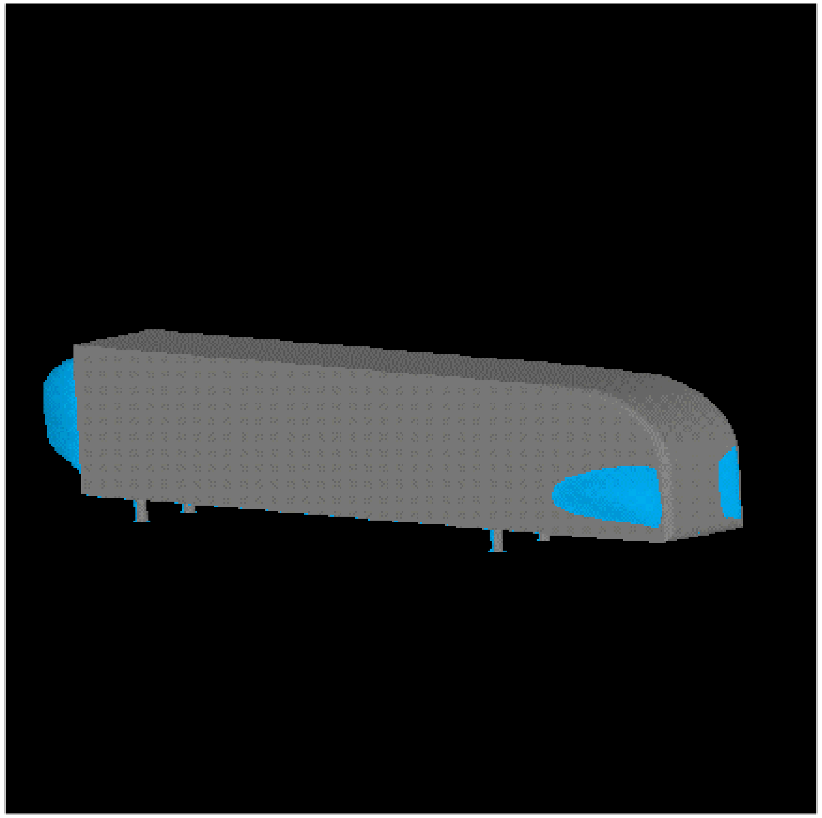
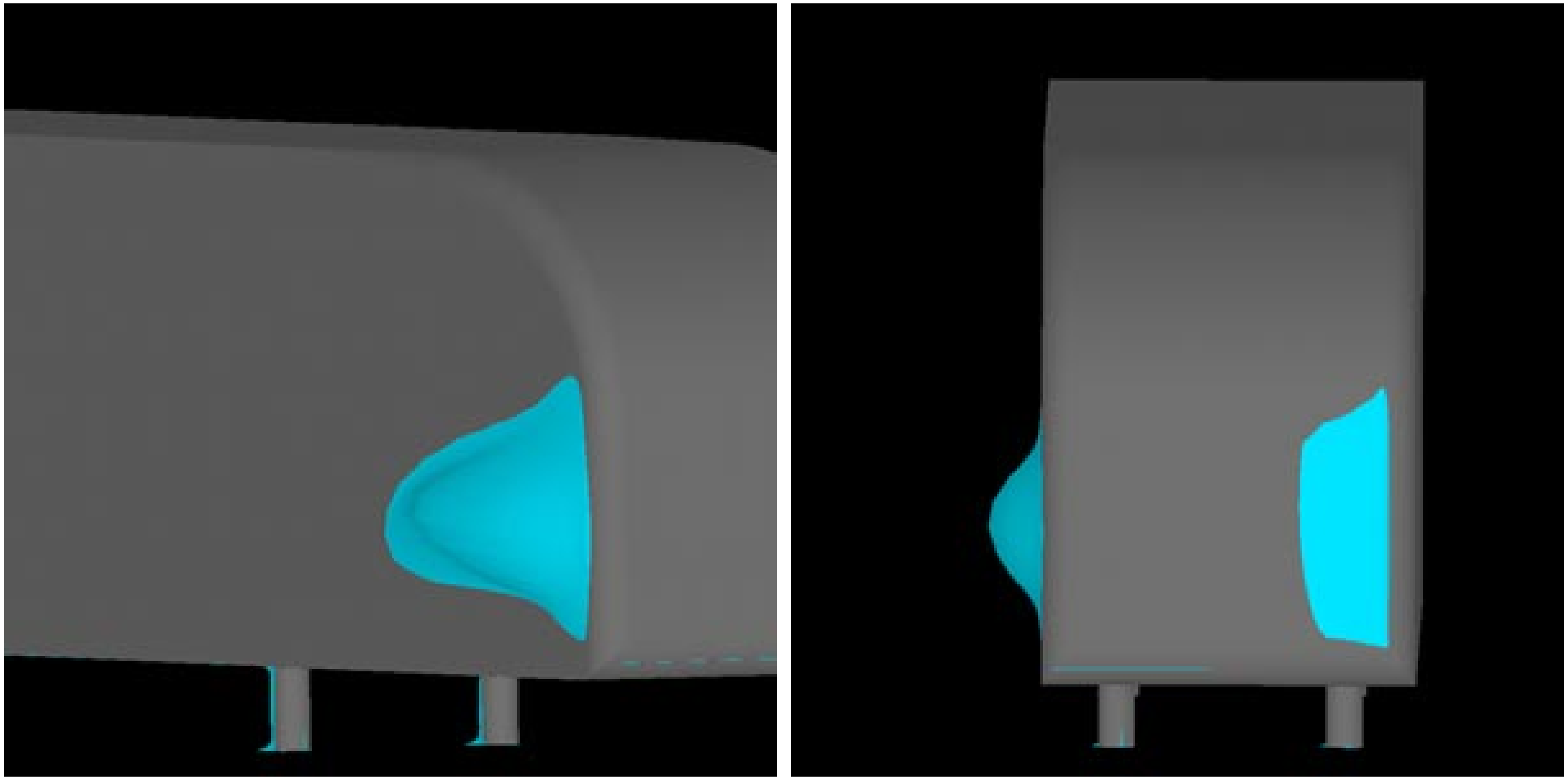


Separation Bubble, Leeward Side, 10° yaw, ...

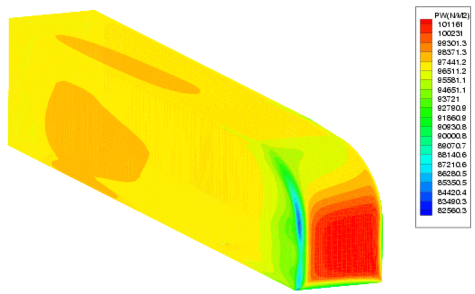
Iso-Surface u = -0.001 (m/s)

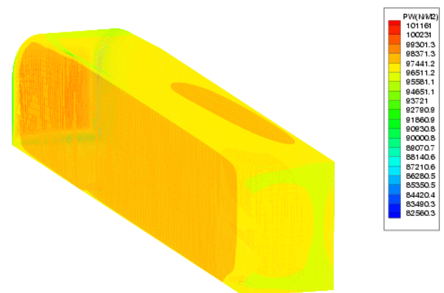


Pressure Distribution on the Surface

10° yaw

NASA





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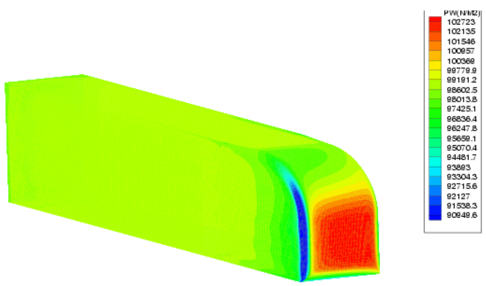
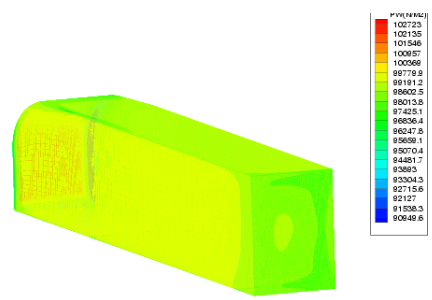
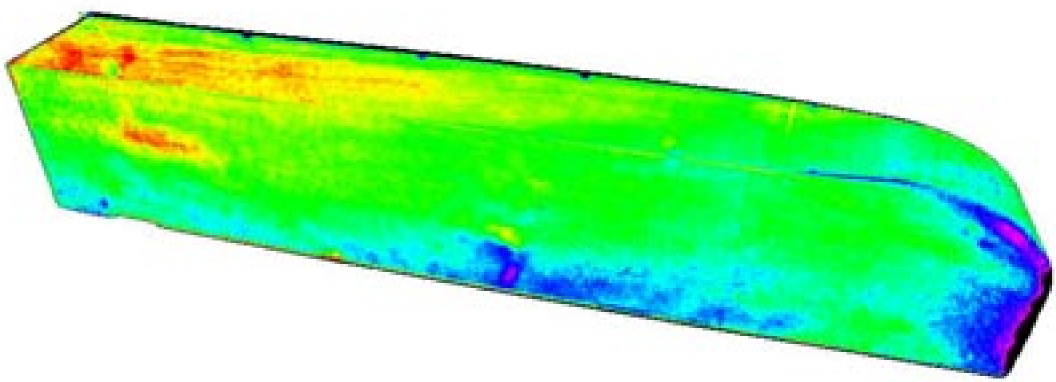




Pressure Sensitive Paint (NASA)

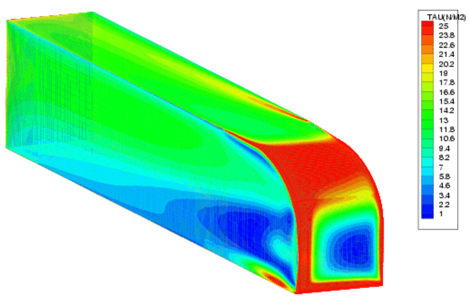
10° yaw

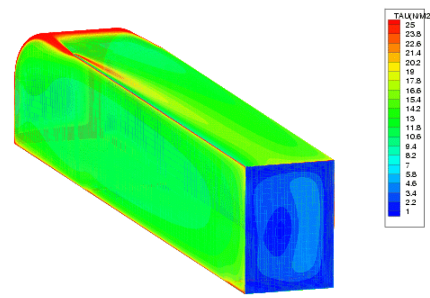


Shear Stress Distribution on the Surface

10° yaw

NASA





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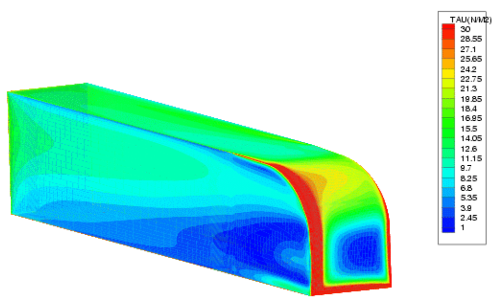
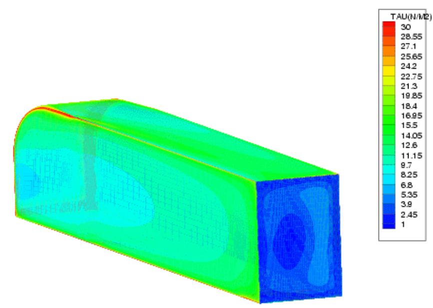




Concluding Remarks

- It was important (for validation purposes) to perform "tunnel empty" simulation of the NASA 7x10 tunnel to obtain proper boundary conditions for GTS simulation
- Two yaw angles (0º and 10º) were computed and the result for the 0º yaw was compared to NASA data
- There is a question of how C_p should be computed to be consistent with the experimental calculation (current method introduces data reduction uncertainty)

Sandia Near Term Tasks

- Complete 0 & 10 yaw simulations and compare results to NASA 7′x10′ experimental data
- Initiate Boattail Plate calculations
- Perform Grid Convergence Studies on 10º yaw case
- Initiate simulations for additional yaw angles to obtain “Wind Averaged Drag Coefficient”
- Document “effort to date” with NASA configuration in technical report (FY01)

TRUCK AERODYNAMICS:

PROGRESS IN CODE DEVELOPMENT RELATED TO TRUCK AERODYNAMICS

Tim Dunn   Rose McCallen   Dan Flowers
Lawrence Livermore National Laboratory

March 16, 2000

University of California
Lawrence Livermore National Laboratory

Our goal is numerical solutions of the Compressible and Incompressible N-S Equations.

Status:

Compressible	In production mode. Enhancements continually being made.
Incompressible	Currently in development. Working for small problems. Working up to large problems.

Common Themes:

Finite Element Method (FEM)

Unstructured Grid

Large-Eddy Simulation

Time-Accurate

- **Explicit Time-Stepping**

ADVANTAGES/DISADVANTAGES OF THE COMPRESSIBLE VS. INCOMPRESSIBLE EQUATIONS.

Compressible Flow

- **Large Mach numbers OK**
- **Time-step limited by speed of sound**

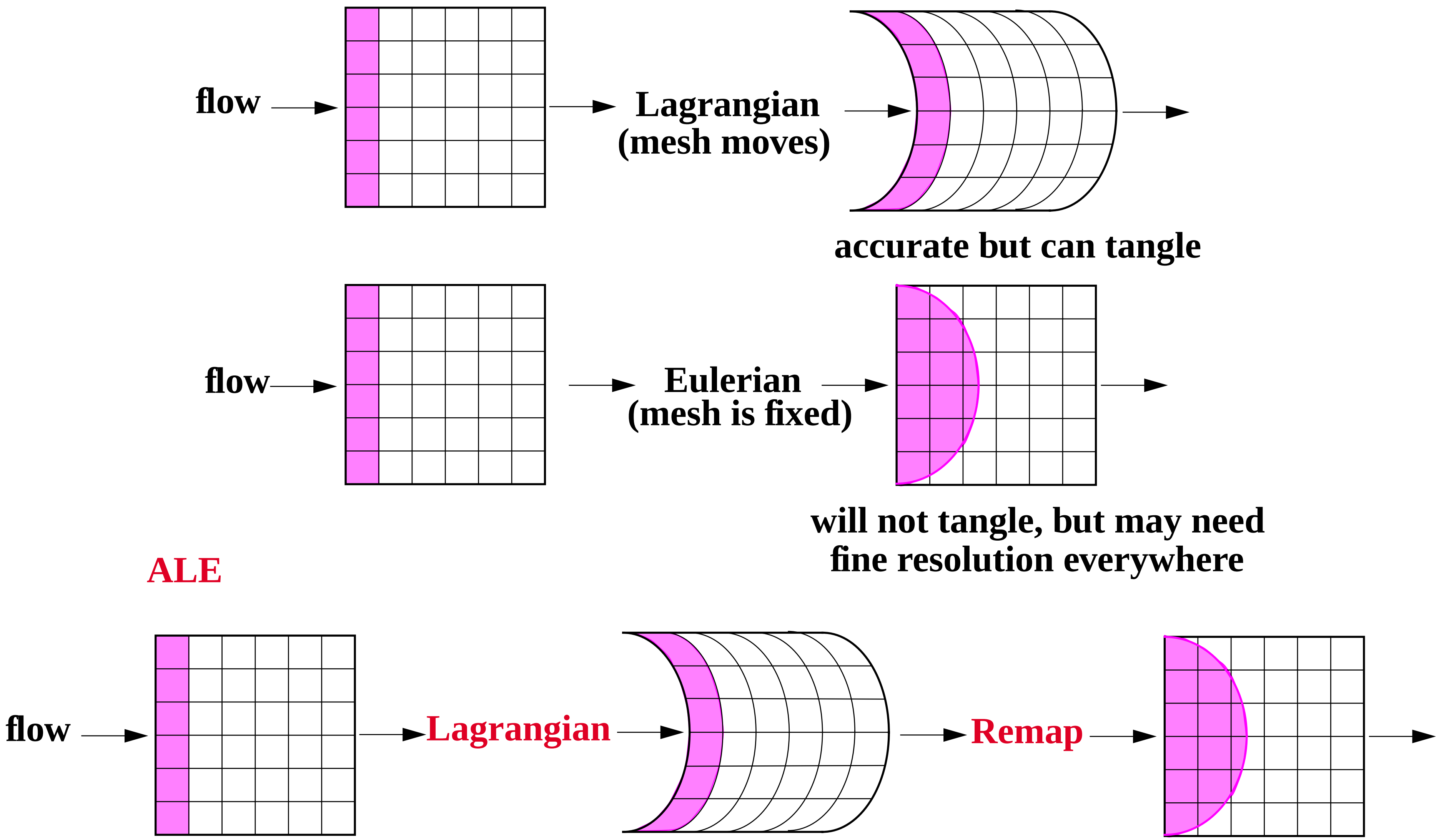
$$\left[\Delta t \sim \frac{1}{a}\right]$$

Incompressible Flow

- **Small Mach numbers only (M < 0.1-0.3)**
- **Time-step limited by local flow velocity**

$$\left[\Delta t \sim \frac{1}{u}\right]$$

The Compressible Flow uses an Arbitrary Lagrangian Eulerian Formulation.



THE INCOMPRESSIBLE FLOW USES AN EULERIAN FORMULATION.

Galerkin Finite-Element Method

- **8-node Hexahedral Elements**
- **Tri-linear Basis Functions for Velocity**
- **Piecewise Constant Pressure**
- **Single Point Integration**

The Incompressible Flow Equations

Conservative Form

Mass $$\frac{\partial u_\alpha}{\partial x_\alpha} = 0$$

$$\tau_{\alpha\beta} = -P\delta_{\alpha\beta} + \nu\frac{\partial u_\alpha}{\partial x_\beta}$$

Momentum $$\frac{\partial u_\alpha}{\partial t} + u_\beta\frac{\partial u_\alpha}{\partial x_\beta} = \frac{\partial \tau_{\alpha\beta}}{\partial x_\beta}$$

$$P = \frac{p}{\rho}$$

Variational Form

Mass $$\int_\Omega w\frac{\partial u_\alpha}{\partial x_\alpha} = 0$$

Momentum $$\int_\Omega v\left(\frac{\partial u_\alpha}{\partial t} + u_\beta\frac{\partial u_\alpha}{\partial x_\beta}\right) + \int_\Omega \tau_{\alpha\beta}\frac{\partial v}{\partial x_\beta} = \int_{\partial\Omega} v f_\alpha$$

$$f_\alpha = n_\beta\tau_{\alpha\beta} = n_\beta\left(-P\delta_{\alpha\beta} + \nu\frac{\partial u_\alpha}{\partial x_\beta}\right)$$

THE INCOMPRESSIBLE FLOW EQUATIONS
DISCRETE FORM

Variable Expansion

$$u_{\alpha}^{h}(x,t) = \sum_{j=1}^{N} u_{\alpha}^{j}(t)\phi_{j}(x) \qquad v = \phi_{i}(x),\ i = 1, N$$

$$ {}^{h}(x,t) = \sum_{j=1}^{M} P_{j}(t)\psi_{j}(x) \qquad w = \psi_{i}(x),\ i = 1, M$$

Mass

$$\left(\int_{\Omega}\psi_{i}\frac{\partial\phi_{j}}{\partial x_{\alpha}}\right)u_{\alpha}^{\ j} = 0$$

Momentum

$$\left(\int_{\Omega}\phi_{i}\phi_{j}\right)\frac{\partial u_{\alpha}^{\ j}}{\partial t} + \left(u_{\beta}^{k}\int_{\Omega}\phi_{i}\phi_{k}\frac{\partial\phi_{j}}{\partial x_{\beta}}\right)u_{\alpha}^{\ j} + \left(\int_{\Omega}\upsilon\frac{\partial\phi_{i}}{\partial x_{\beta}}\frac{\partial\phi_{j}}{\partial x_{\beta}}\right)u_{\alpha}^{\ j}$$

$$-\left(\int_{\Omega}\psi_{j}\frac{\partial\phi_{i}}{\partial x_{\alpha}}\right)P^{\ j} = \int_{\partial\Omega}\phi_{i}\ f_{\alpha}$$

THE INCOMPRESSIBLE FLOW EQUATIONS
MATRIX FORM

$$C^T \underline{v} = 0$$

$$M\dot{u} + [K + N(u)]u + CP = F$$

OR

$$\begin{bmatrix} M' & C \\ C^T & 0 \end{bmatrix} \begin{bmatrix} v \\ P \end{bmatrix} = \begin{bmatrix} F' \\ 0 \end{bmatrix}$$

where

$$\underline{v} = \underline{u}^{n+1} - \underline{u}^n \qquad M' = \frac{M}{\Delta t} \qquad F' = F - [K + N(u)]u$$

$$C = \begin{bmatrix} c_{in(1)} \\ c_{in(2)} \\ c_{in(3)} \end{bmatrix}; c_{in(\alpha)} = \int_\Omega \psi_n \frac{\partial \phi_i}{\partial x_\alpha} \qquad M = \begin{bmatrix} m_{ij} & 0 & 0 \\ 0 & m_{ij} & 0 \\ 0 & 0 & m_{ij} \end{bmatrix}; m_{ij} = \int_\Omega \phi_i \phi_j$$

THE MATRIX IS ASSEMBLED AND SOLVED USING THE FEI DEVELOPED AT SANDIA NATIONAL LAB.

Matrix Assembly

- **FEI (SNL)**

Solvers

- **ISIS (SNL)**
- **HYPRE (LLNL)**
- **AZTEC (SNL)**

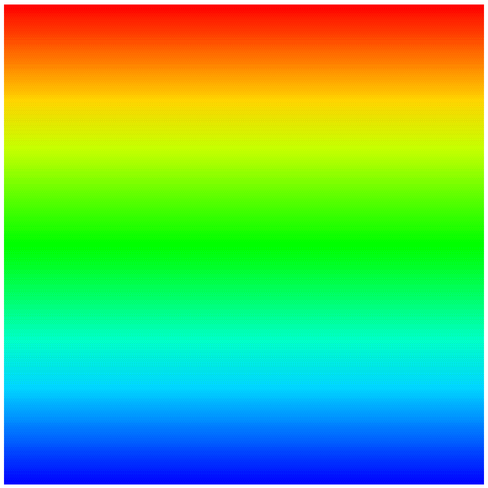
Matrix Solved

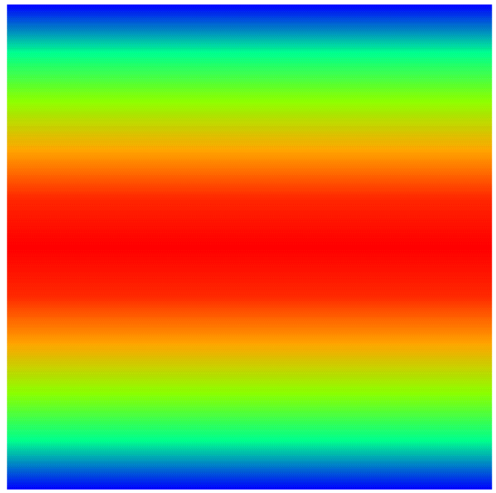
- **Full Matrix**
- **Schur Compliment,** $(C^T M^{-1} C)P = 0$

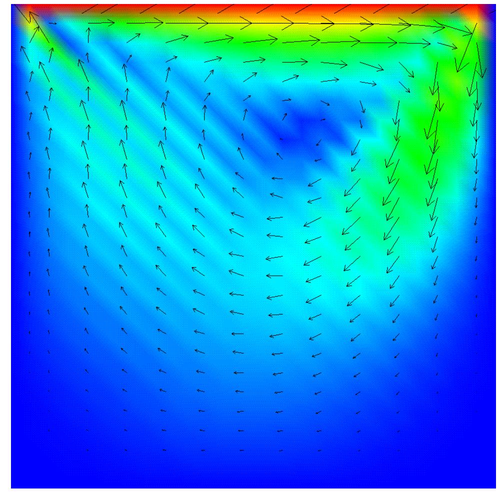
- Difficult to find solvers which efficiently solve our matrix and work in parallel.

We have some validation of
The Incompressible Flow Model.

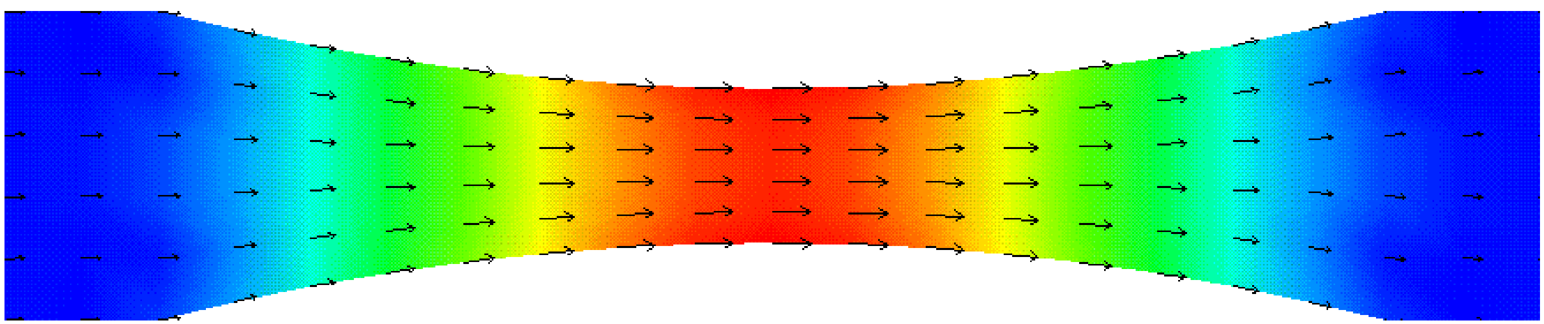
Couette	Poiseuille	Driven Cavity







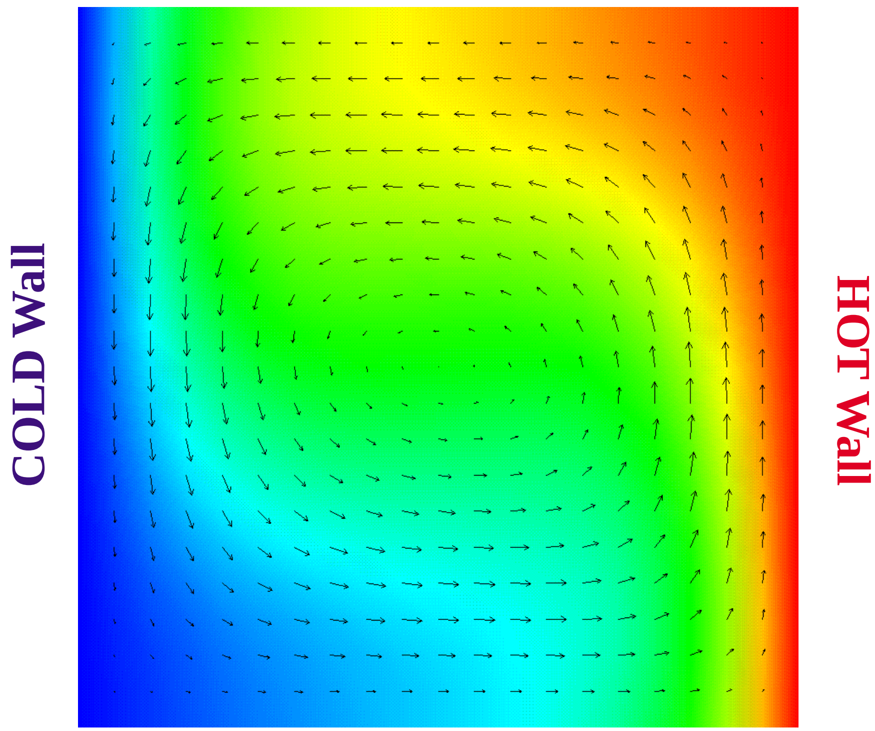
Venturi



MULTIPHYSICS MODELING IS ANOTHER PART OF OUR R&D EFFORT.

Goals: Flow/Structural/Thermal/Chemistry

Status: Flow/Thermal



Thermally Driven Cavity

Temperature Contours

Velocity Vectors

Large Eddy Simulation of NASA 7’ x 10’ Wind Tunnel Tests

Dan Flowers, Rose McCallen, Tim Dunn , Jerry Owens

Lawrence Livermore National Laboratory
Livermore, CA

March 16, 1999

University of California
Lawrence Livermore National Laboratory

*Work performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract W-7405-ENG-48.

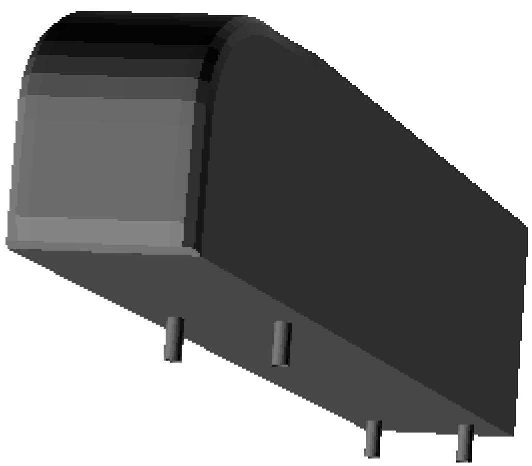
Introduction

Goal

To develop simulation tools which can accurately predict the flow-field of heavy vehicles. These tools can be applied to investigating drag reduction strategies.

Approach

Carefully validate the simulations with well characterized experimental data



The flow around a truck is difficult to simulate

Flow is time dependent, 3D with a wide range of scales

- Boundary layers transition and separate
- Flow tripped by head lamps, grab handles, etc.

Chosen approach

- Compressible ALE simulation code
- Large-eddy simulation (LES) using the finite element method (FEM)
  - Captures large scales > Δgrid
  - Approximates small scales < Δgrid
- Explicit Scheme - $\Delta t=(u+a)/\Delta x$

Several approaches are being used to simulate the GTS

SNL

- Reynolds Average Navier-Stokes (RANS)/ Detached Eddy Simulation (DES)
- Compressible Finite Volume Code
- Average "Steady" Solution/Unsteady Solution
- Widely used - may not predict drag correctly

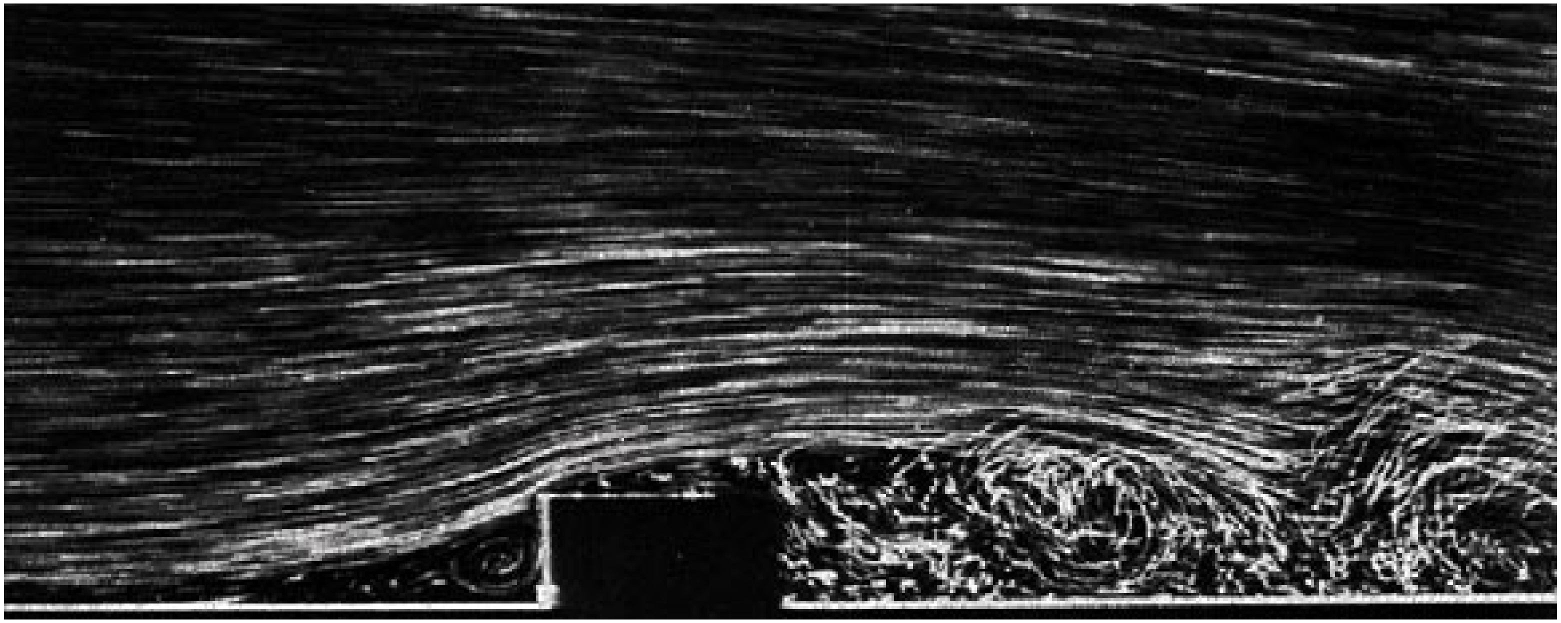
LLNL

- Large Eddy Simulation (LES)
- Compressible Finite Element Code
- Unsteady Solution of large scales/approximation of the small scales
- Computationally intensive

Caltech

- Direct Numerical Simulation/ LES
- Vortex Method
- Gridless
- In development

Turbulent flow contains eddies ranging from large-scale to small-scale



Large-eddy simulation captures the large-scale motion and approximates the small-scale motion.

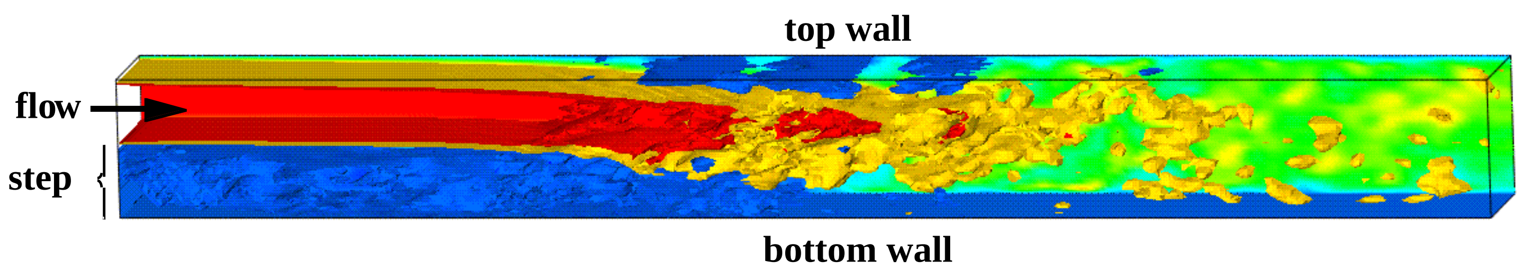
all turbulent motions = large-scale motions + small-scale motions

= 'resolved' scale + 'subgrid' scale

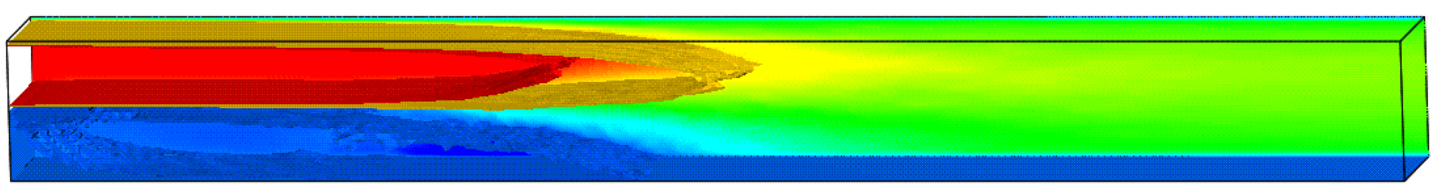
$$u_\alpha = \bar{u}_\alpha + u'_\alpha$$

Streamwise Velocity

LES: instantaneous and/or time-averaged with 1 empirical parameter



RANS: only time-averaged with many empirical parameters

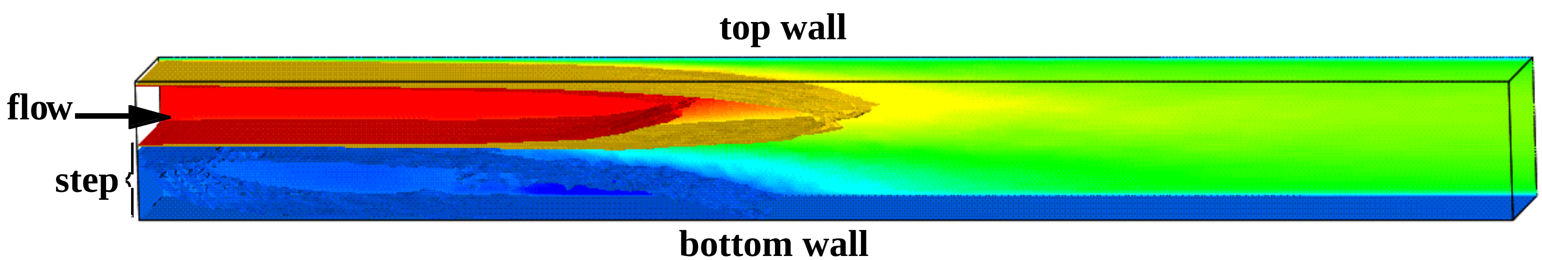


Modeling the unsteady, 3-D vortex shedding in ‘step-flows’ requires innovation

Commercial state-of-the-art

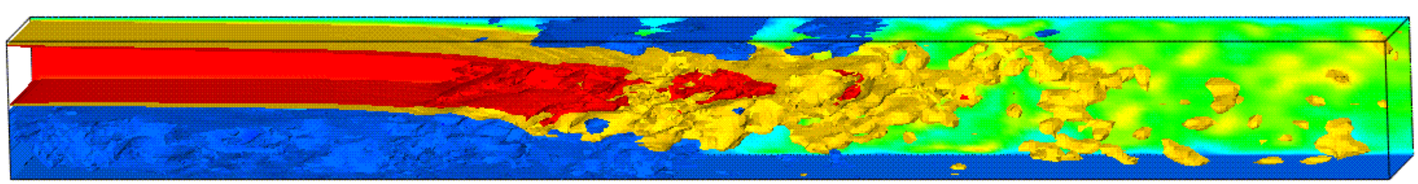
- Reynolds-Averaged Navier-Stokes (RANS) turbulence model
- Many empirical parameters
- 2D, steady, time-averaged solution

Backward-facing step: streamwise velocity



Current leading-edge technology

- Large-eddy simulation (LES) turbulence model
- One empirical parameter (maximum)
- 3D, unsteady solution of vortex shedding



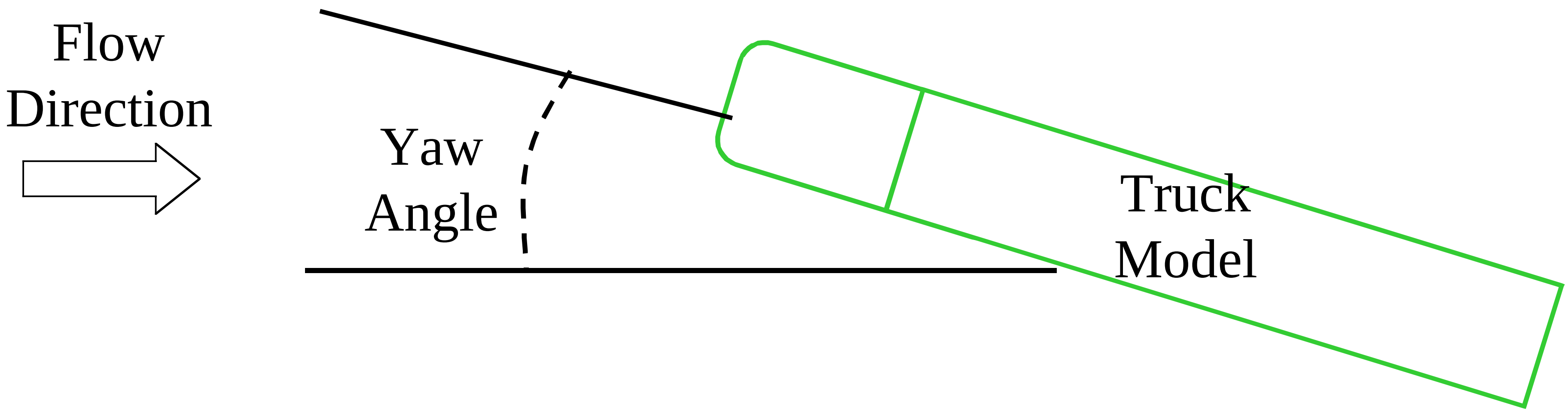
The LES challenges are related to physical as well as numerical modeling.

Boundary layers are very thin	Can’t resolve boundary layers - problem gets too big
	Wall approximations in development
Runtime very long	Evolution is over long time scales
	Parallel computations/solvers required - in development
Analysis	Huge data sets
	Visualization required - in development
	Methods for testing convergence (V&V) in development

Significant development being done by LLNL programs.

NASA wind tunnel tests have been conducted on a simplified truck geometry

- NASA experimental data available for several yaw angles (from 0° to 15°)
- Simulations to be validated with experimental data



Simulations focus on NASA 7’x10’ wind tunnel tests

A Grid of the full 7’x10’ wind tunnel has been developed

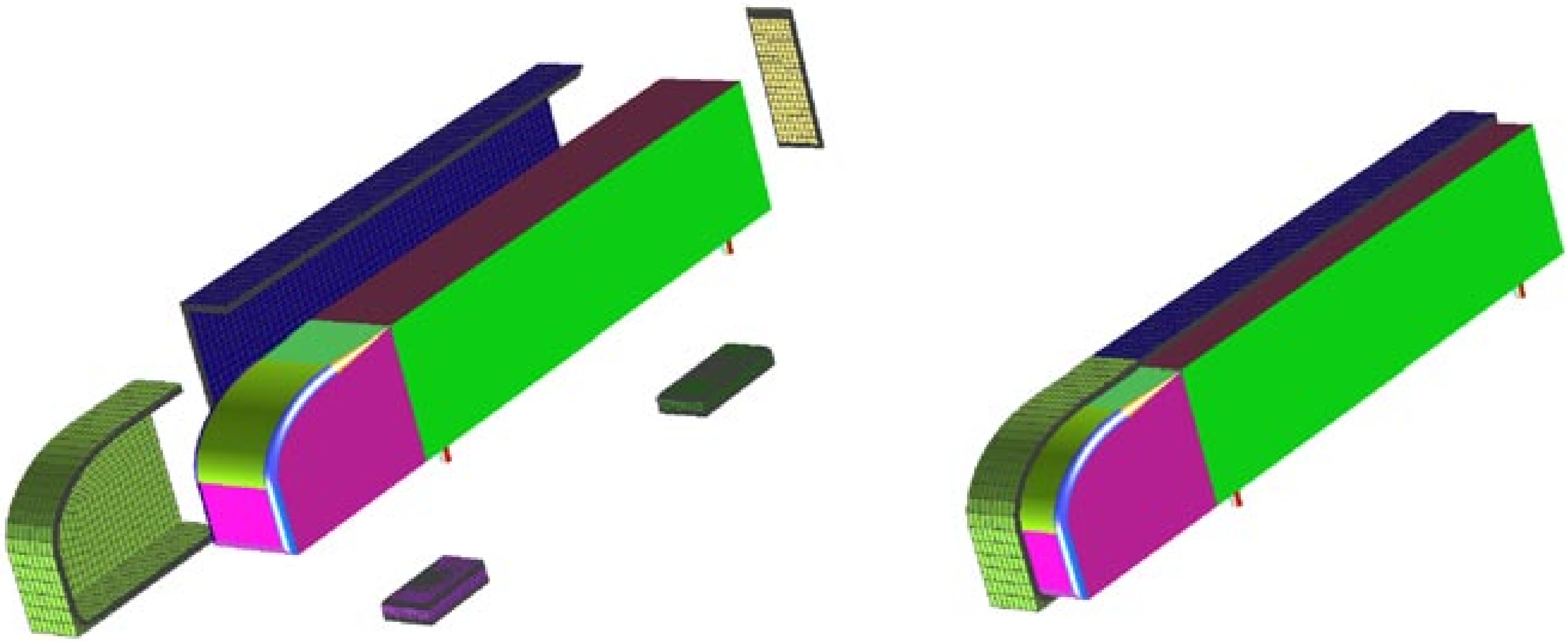
- Scaleable
- Allows for yawing of the model

Currently simulating involves 0° yaw to validate model and study mesh refinement

Compressible/Incompressible simulations for 0° yaw

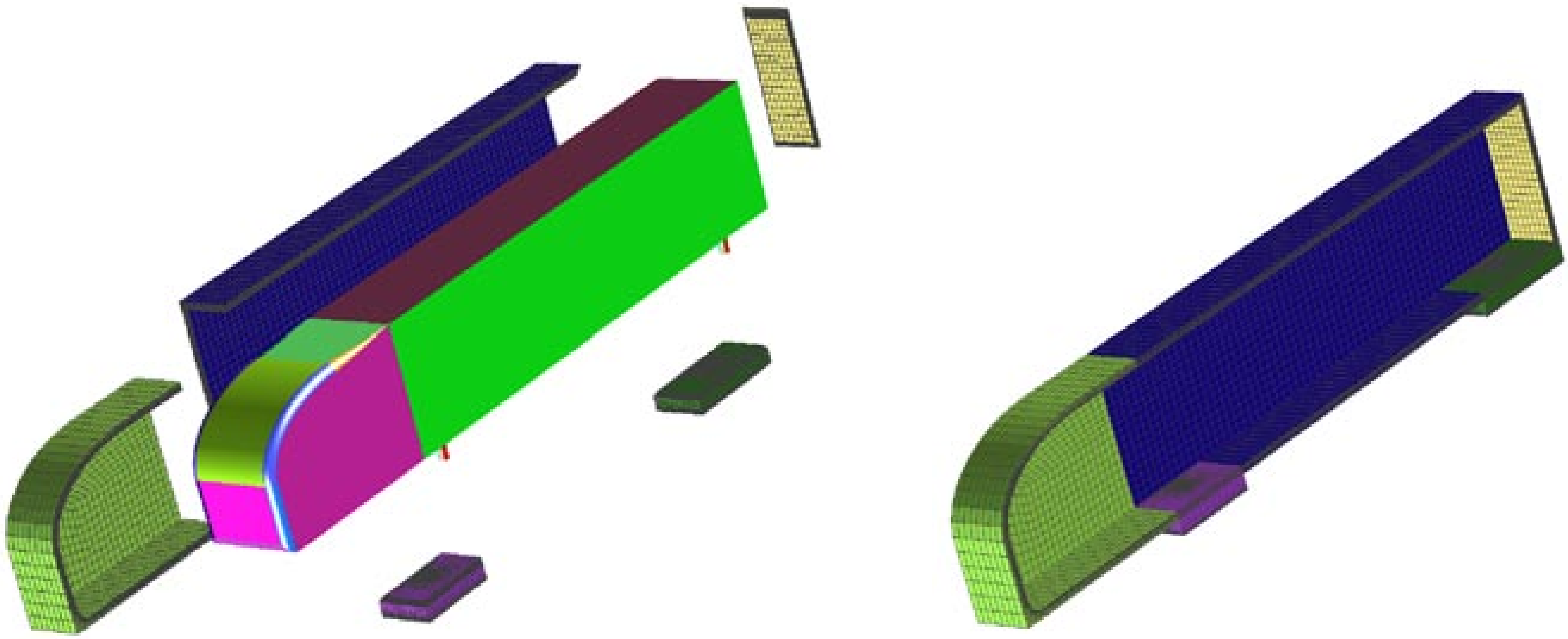
0.3 Million	Completed
2.4 Million	In progress
19 Million	Future
154 Million	Future

0.3 million element mesh



- Unstructured multi-block mesh
- Near body mesh can be refined independently of “Far-Field” mesh
- Full geometry simulated - mesh reflected about symmetry plane

0.3 million element mesh



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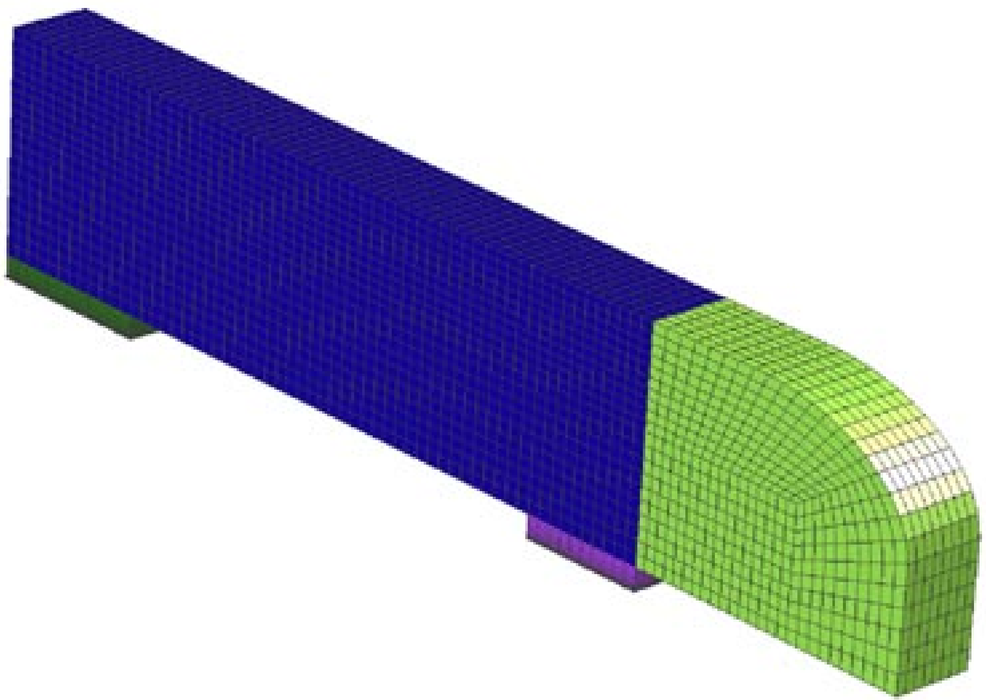
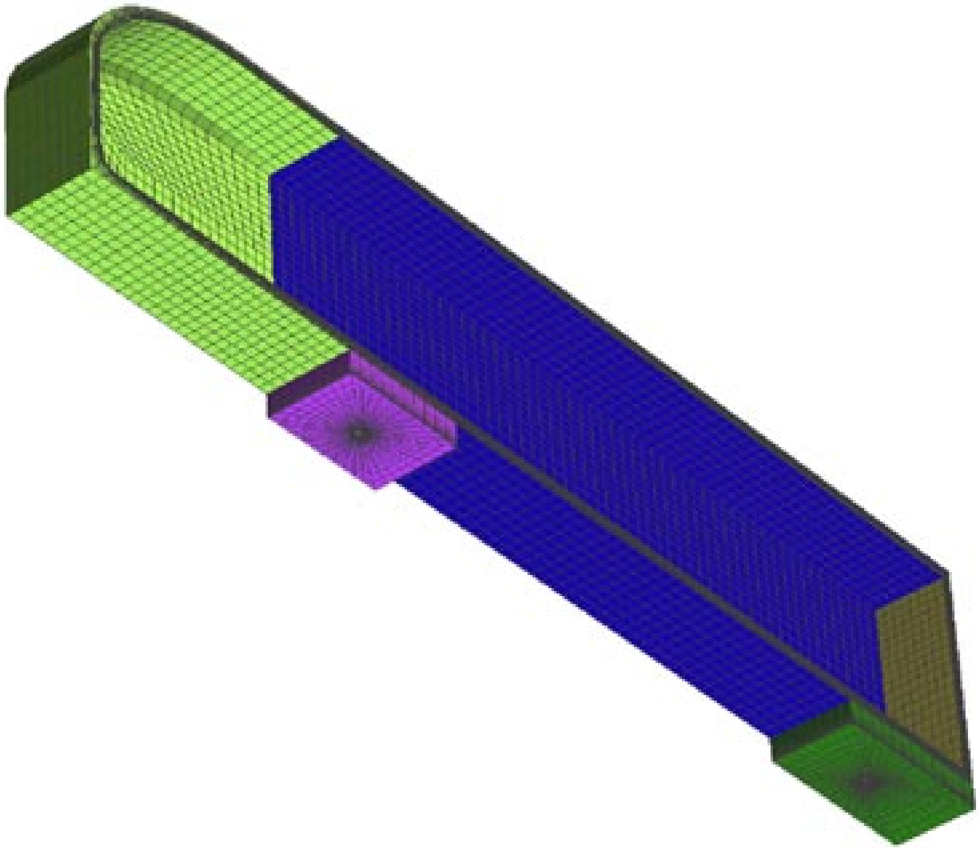
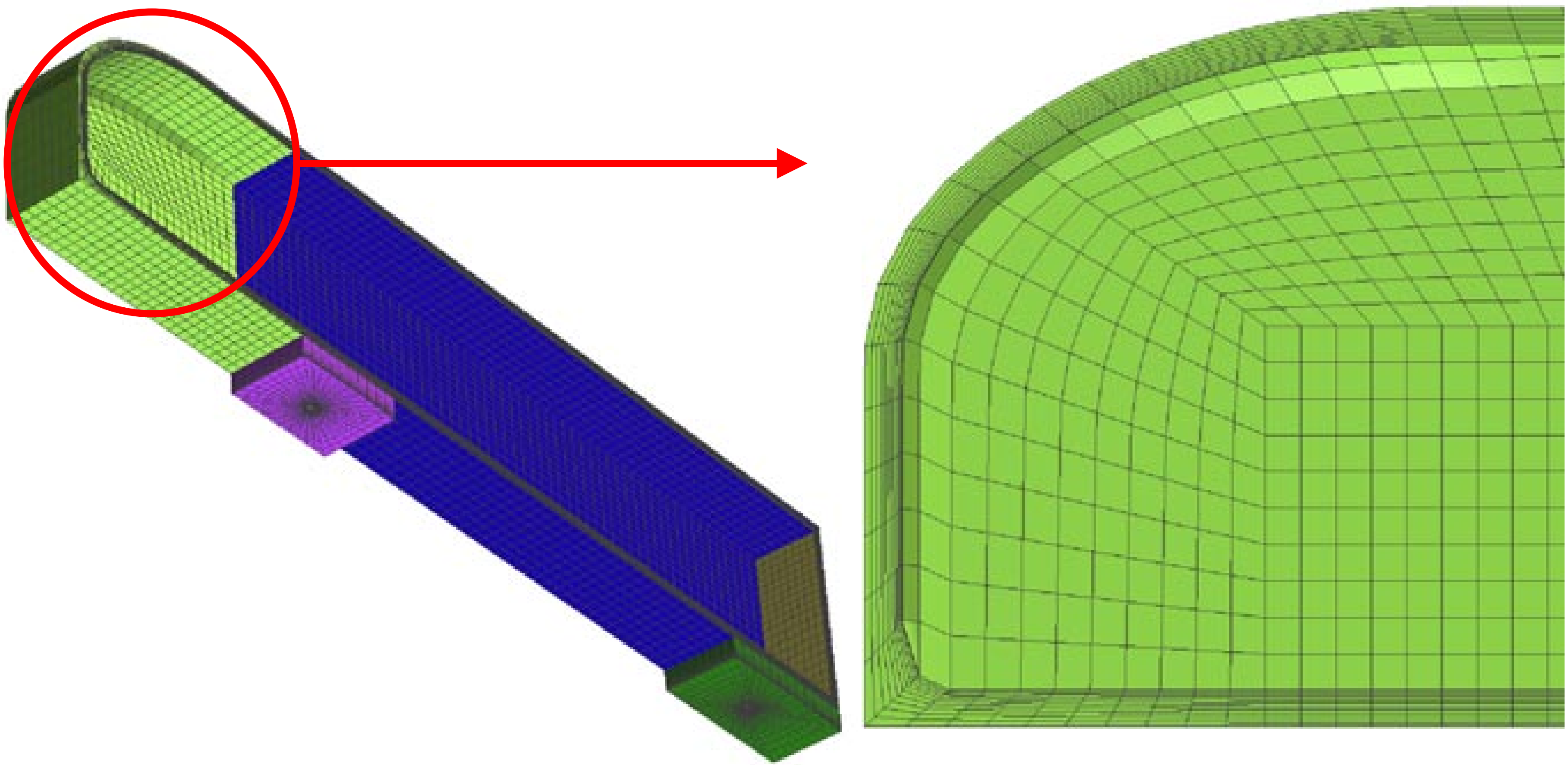
0.3 Million Element Mesh



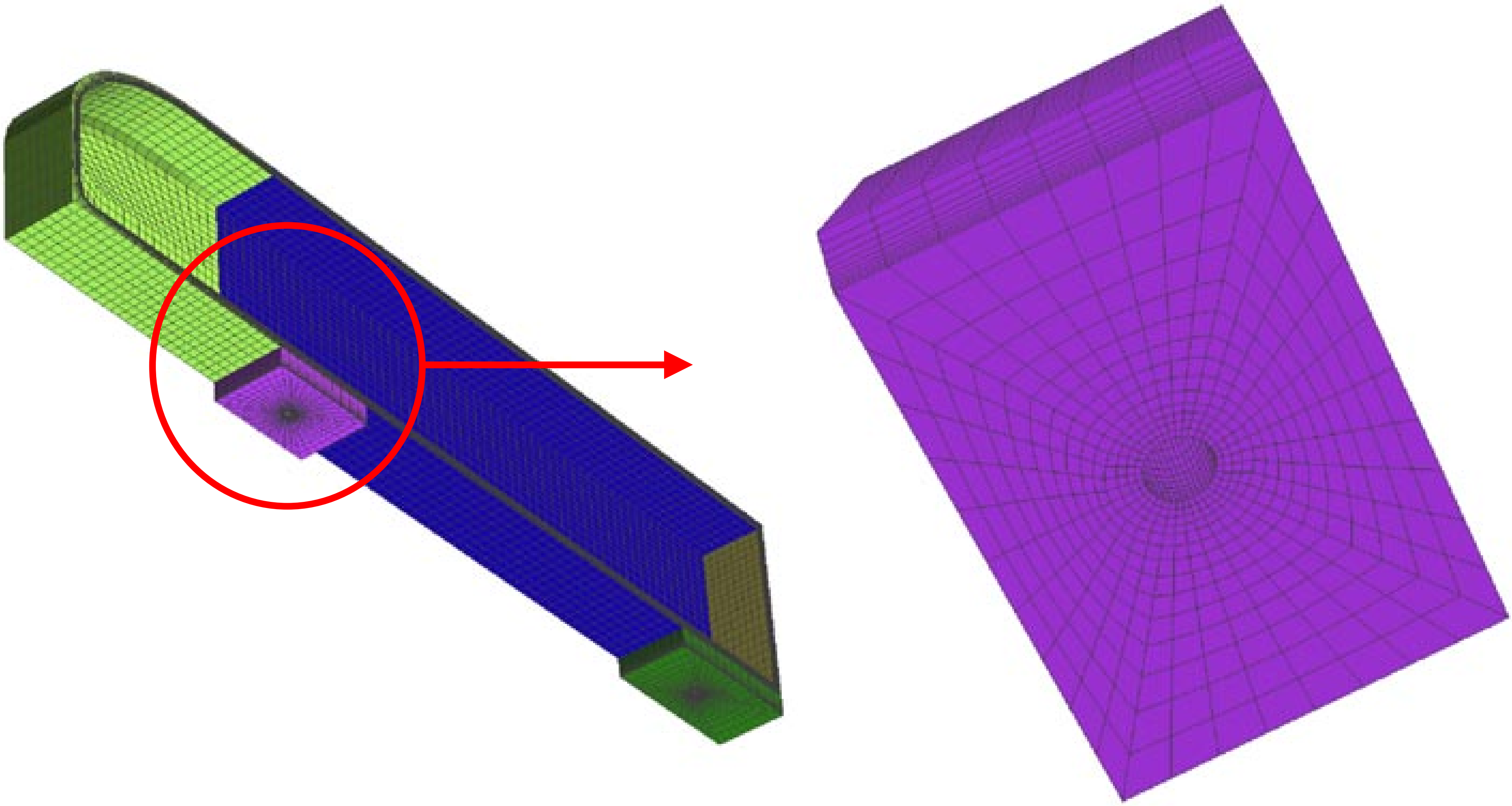
0.3 Million Element Mesh



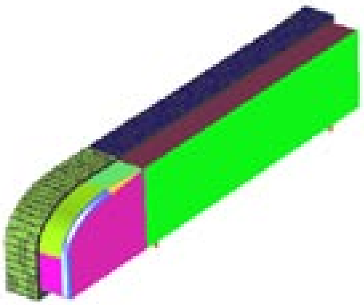
0.3 Million Element Mesh



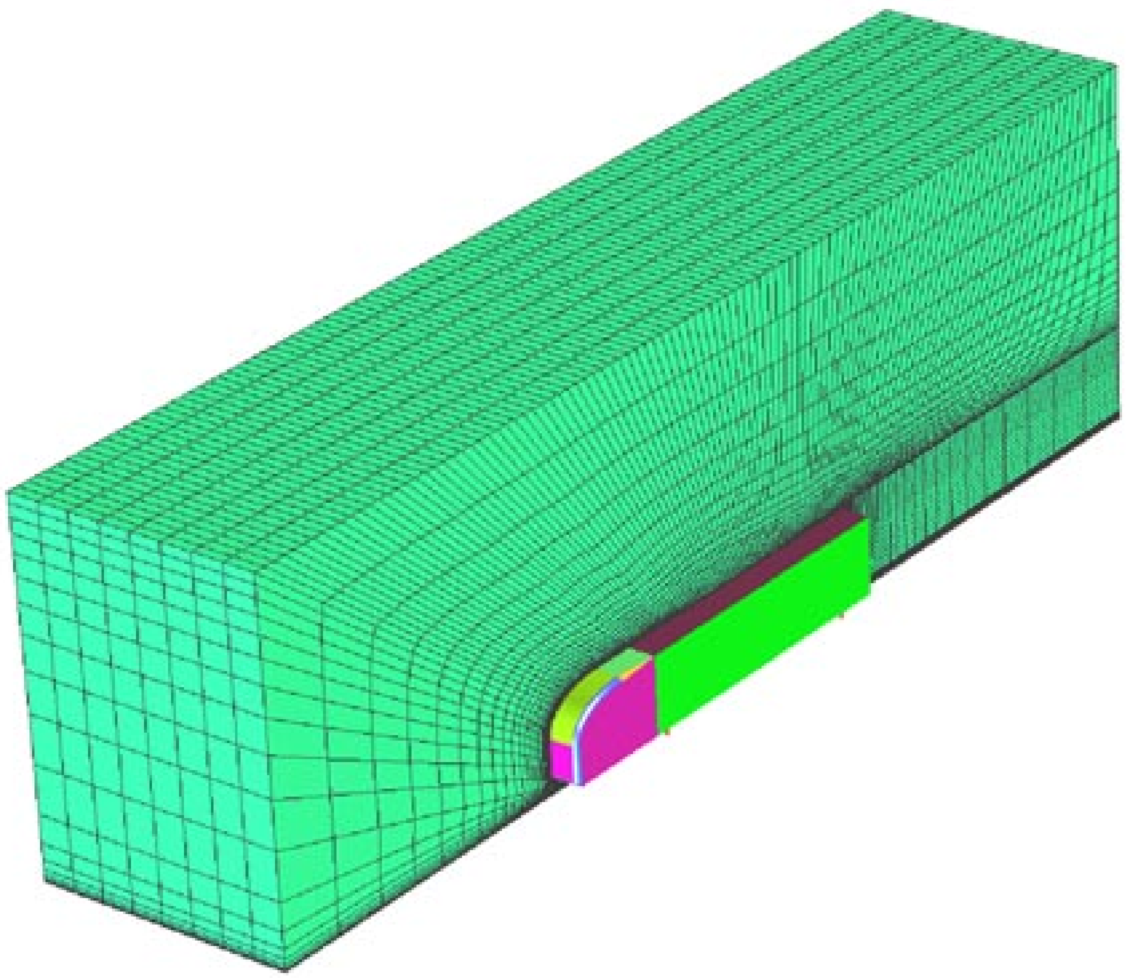
0.3 Million Element Mesh



0.3 million element mesh

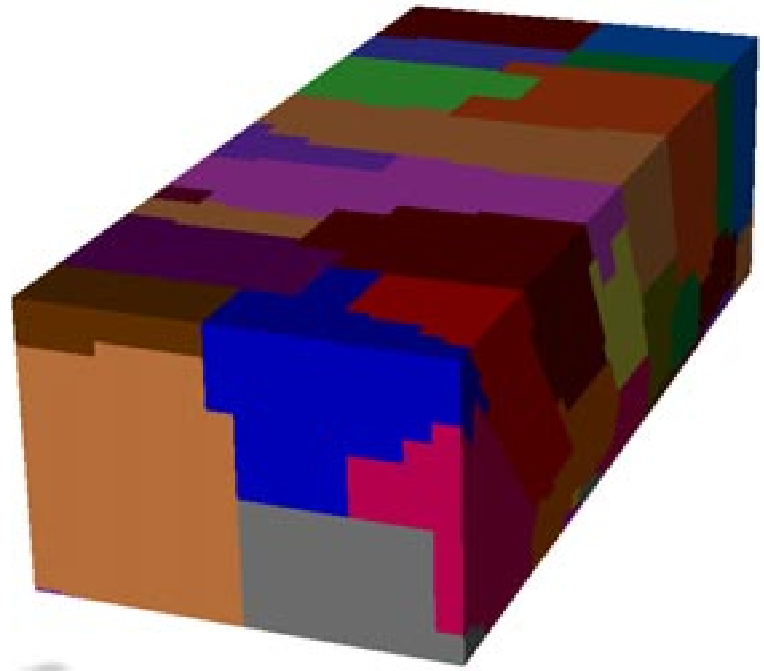


0.3 million element mesh



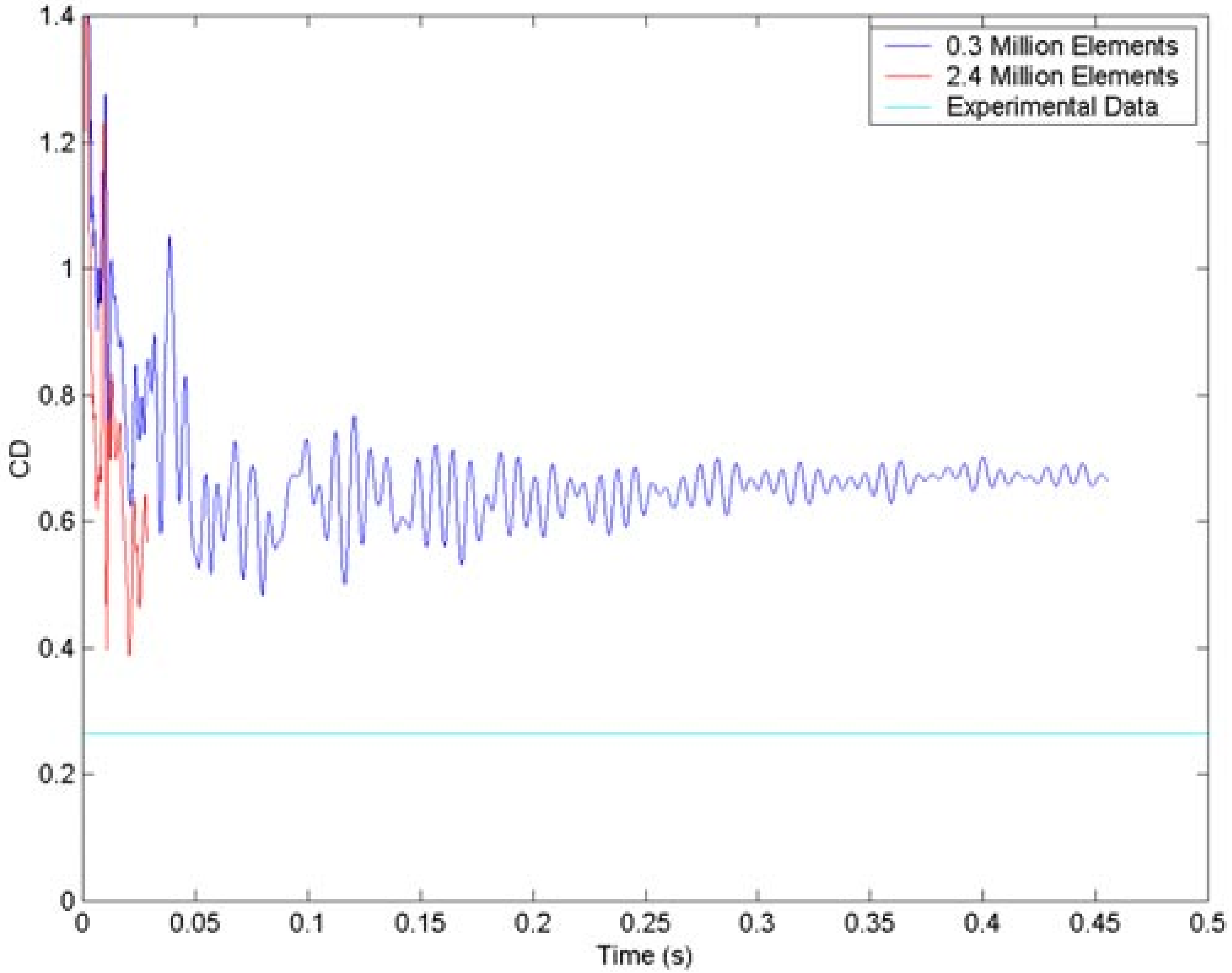
Parallel computation

- Parallel computation necessary because of large number of elements
- Domain decomposition performed using parmetis algorithm
- Simulations are being performed on massively parallel ASCI Blue machine
  - 0.3M Element Mesh (24 processors)
  - 2.4M Element Mesh (148 processors)
  - 19M Element Mesh (~1000 processors)
  - 154M Element Mesh (~ 5000 processors)

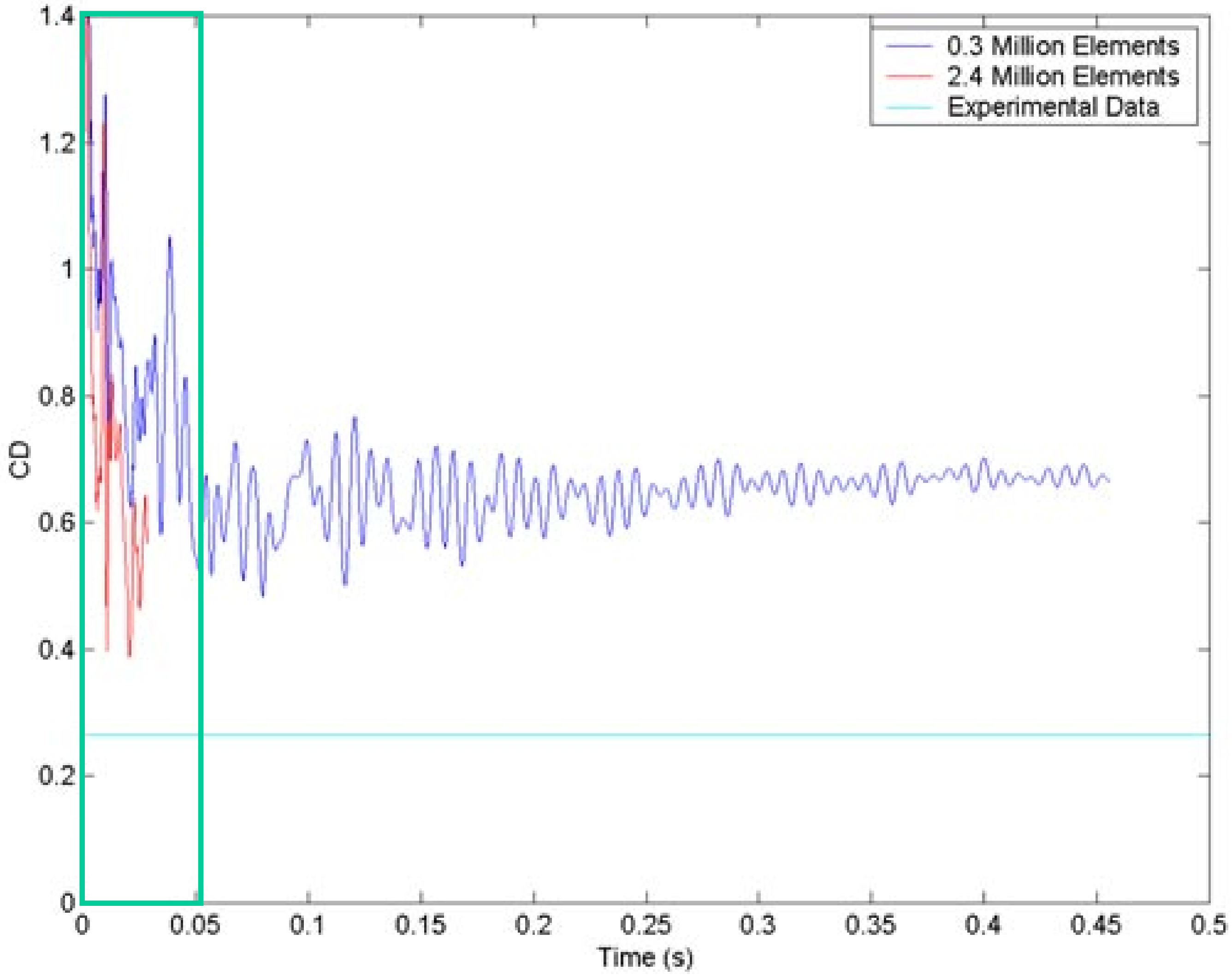


Domain decomposition for 0.3 million element

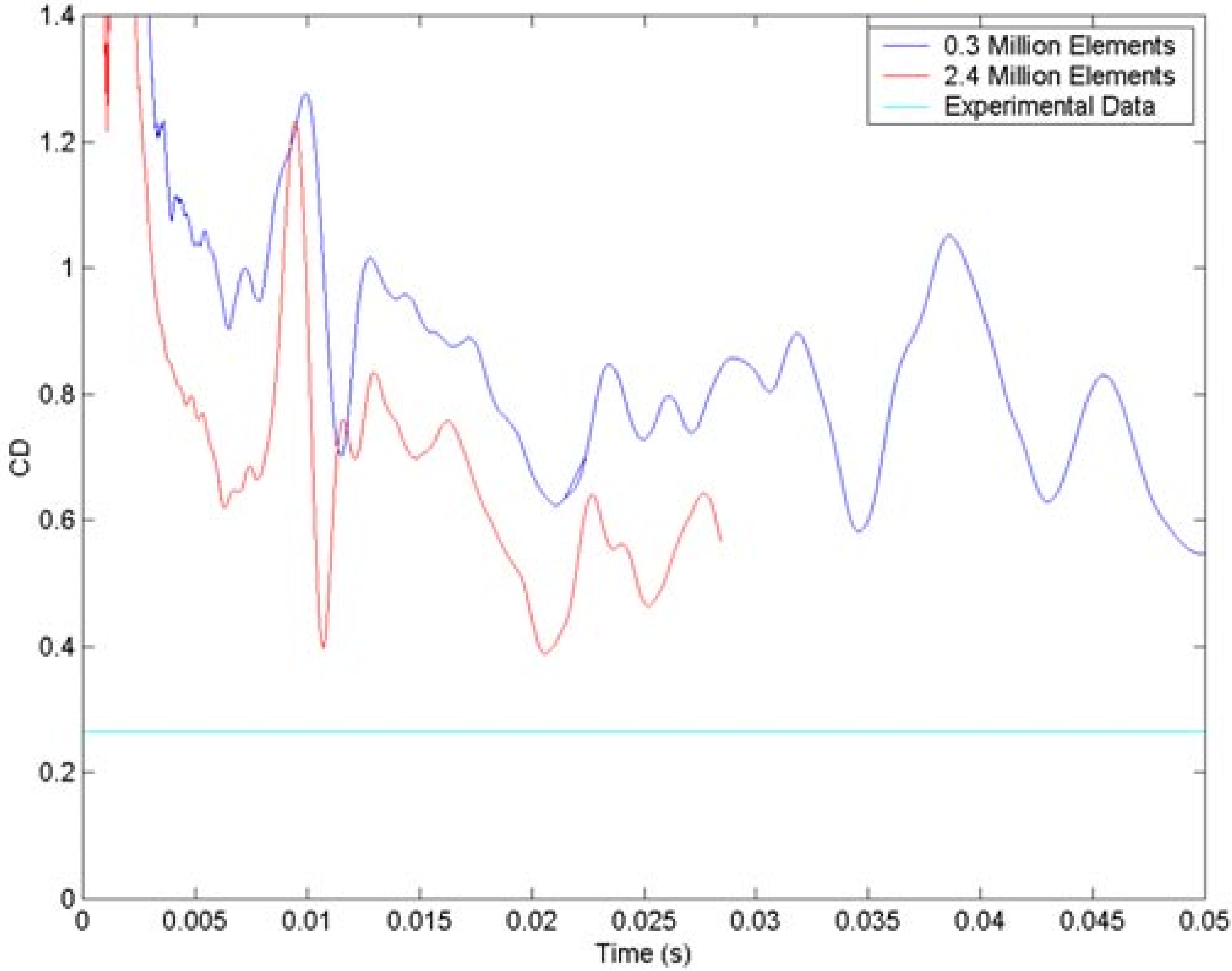
Simulation results - drag coefficient



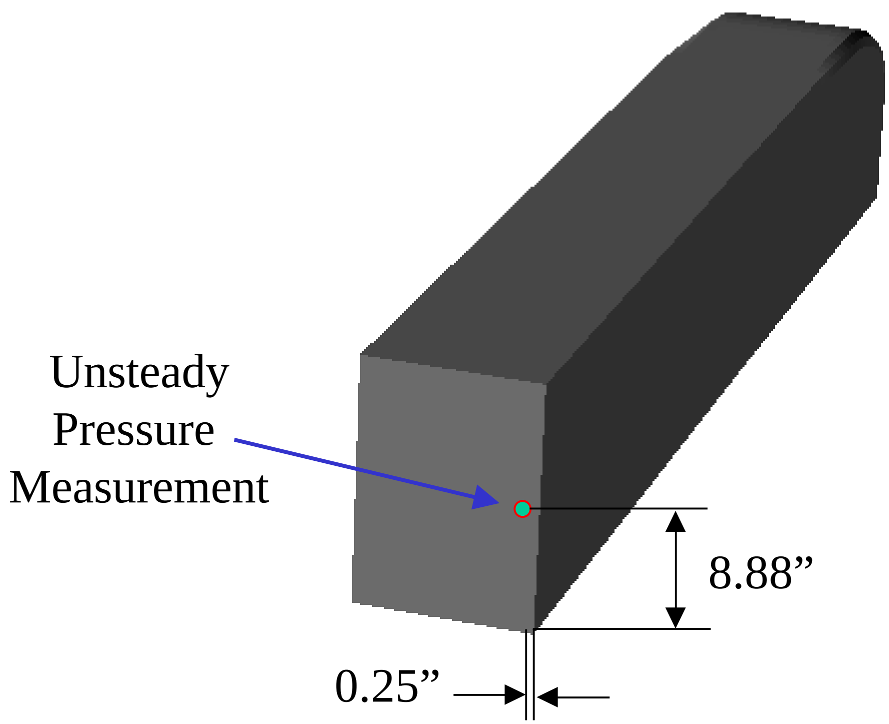
Simulation results - drag coefficient



Simulation results - drag coefficient

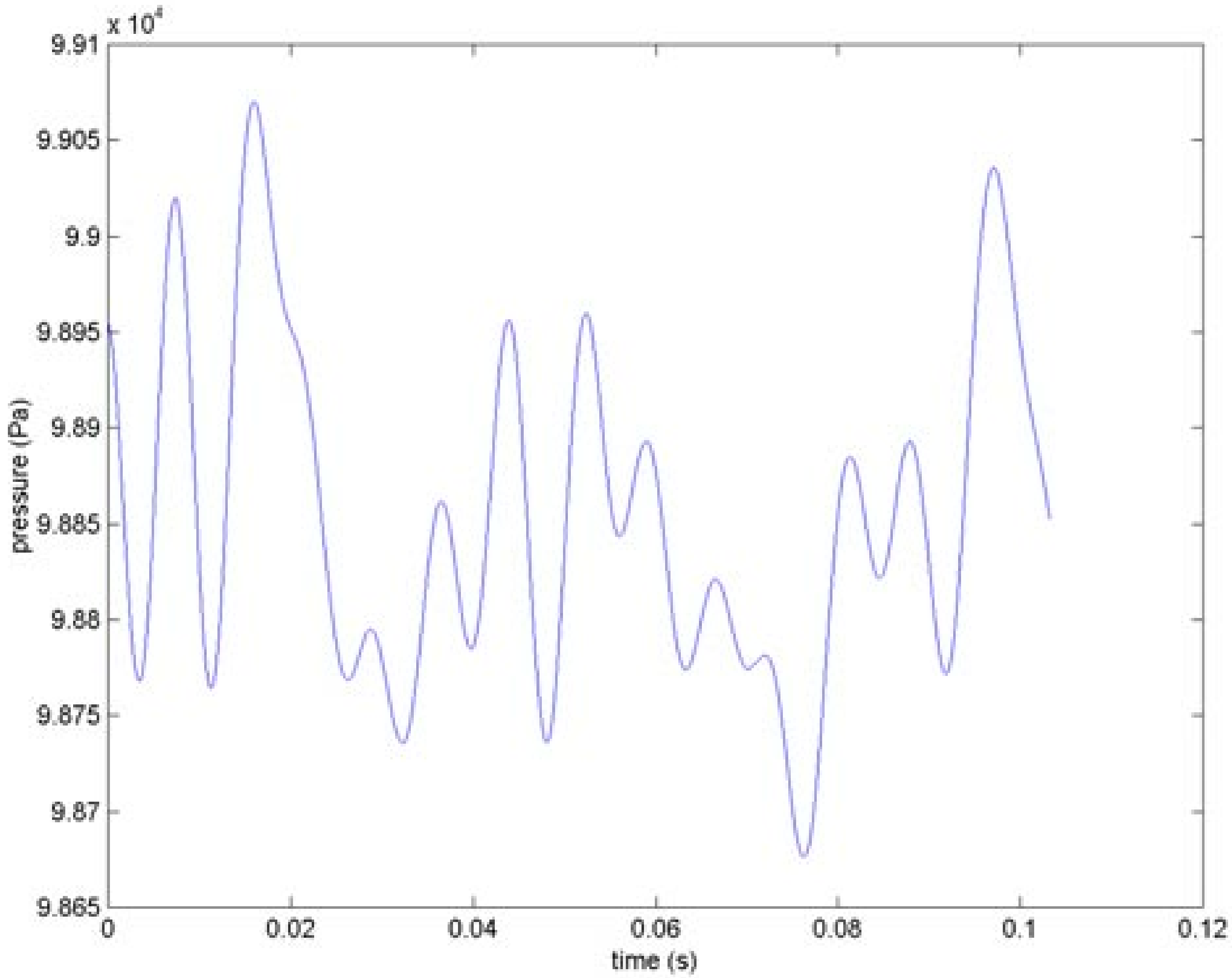


Simulation results - unsteady pressure measurement



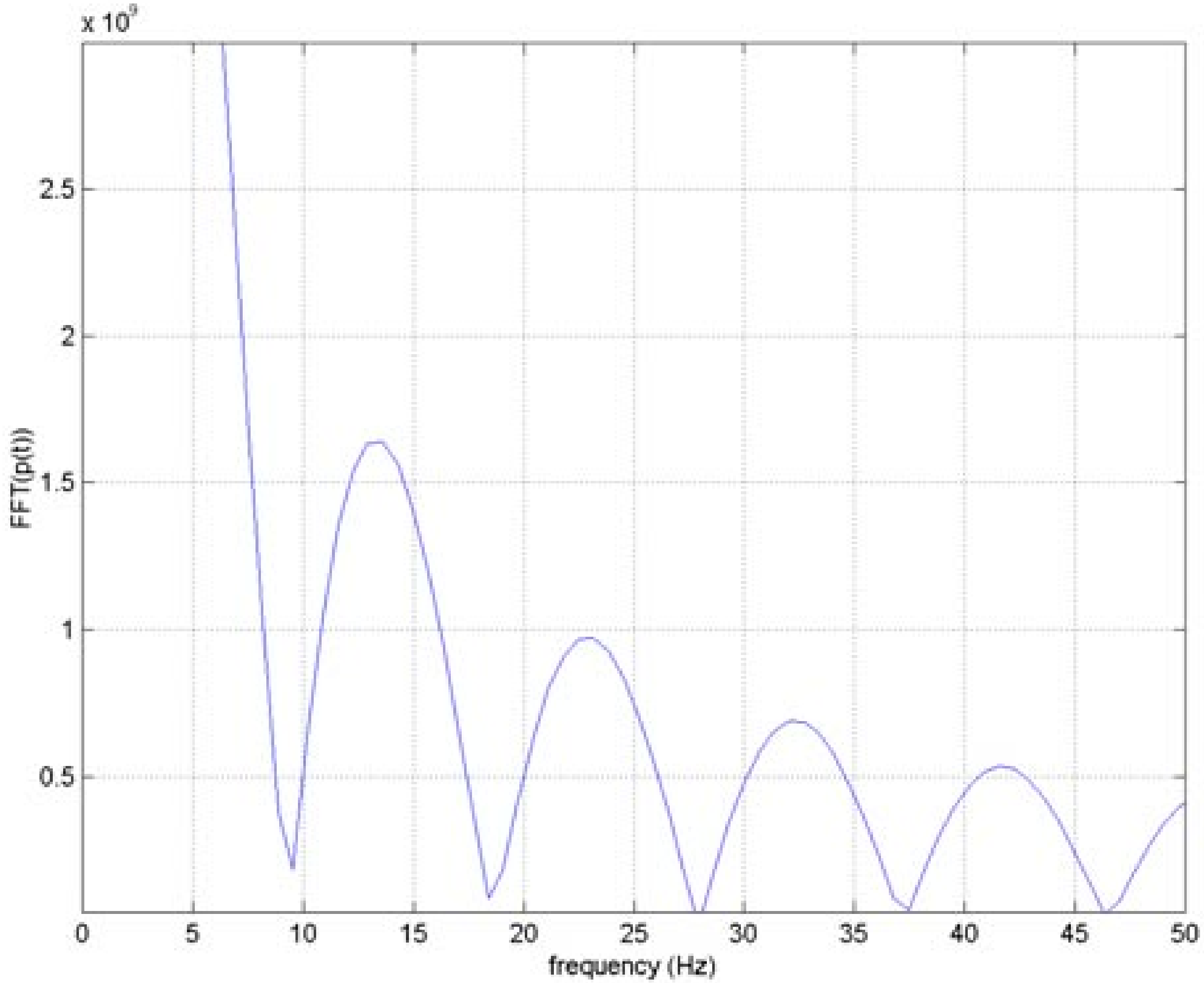
0.3 Million Element Mesh

Simulation results - unsteady pressure measurement



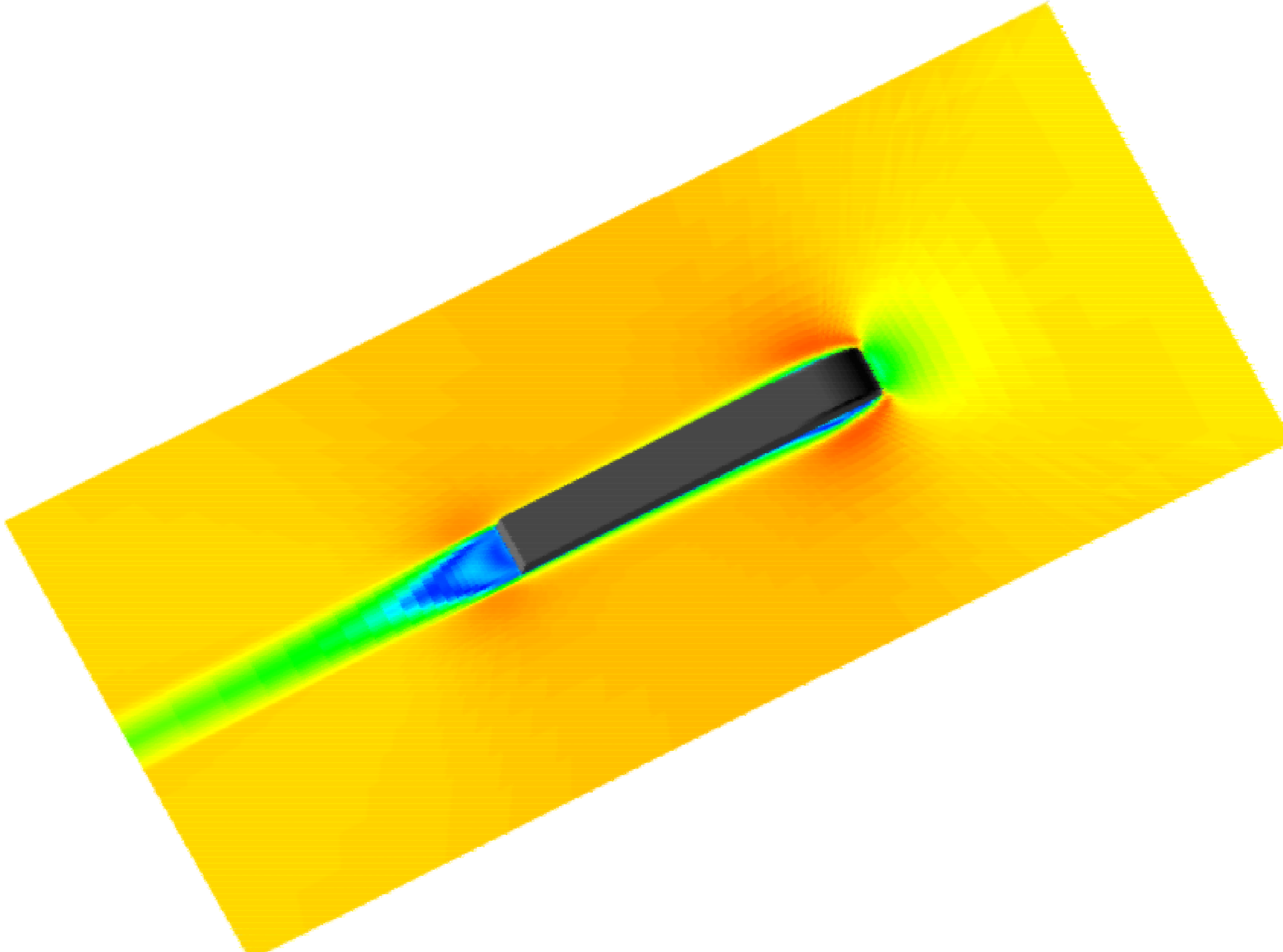
0.3 Million Element Mesh

Simulation results - unsteady pressure measurement



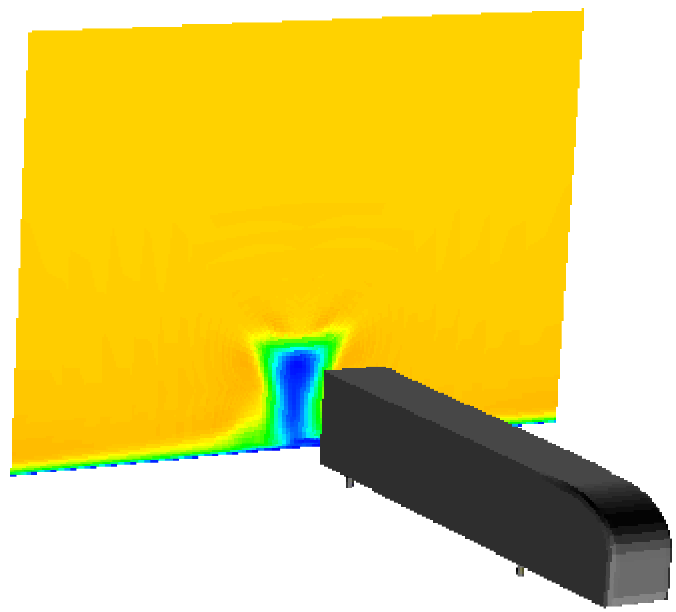
0.3 Million Element Mesh

Simulation results - time average flow field



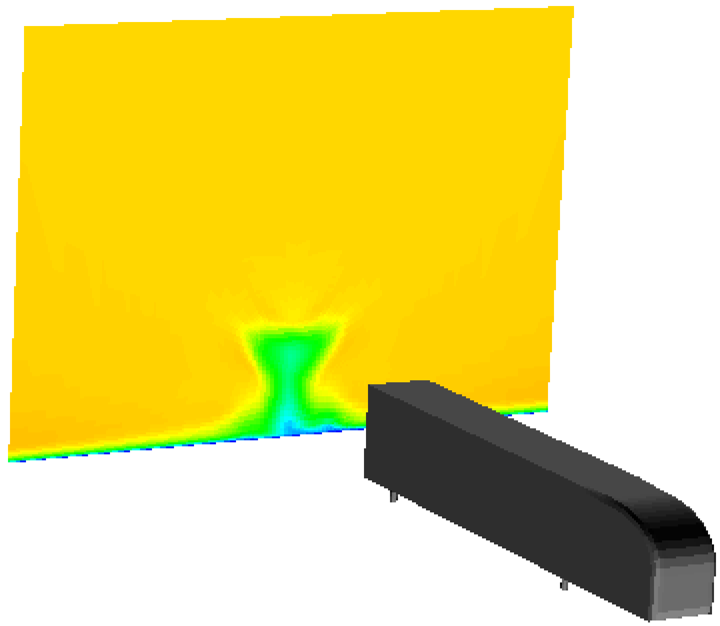
Simulation results - time average flow field

Simulation results - time average flow field



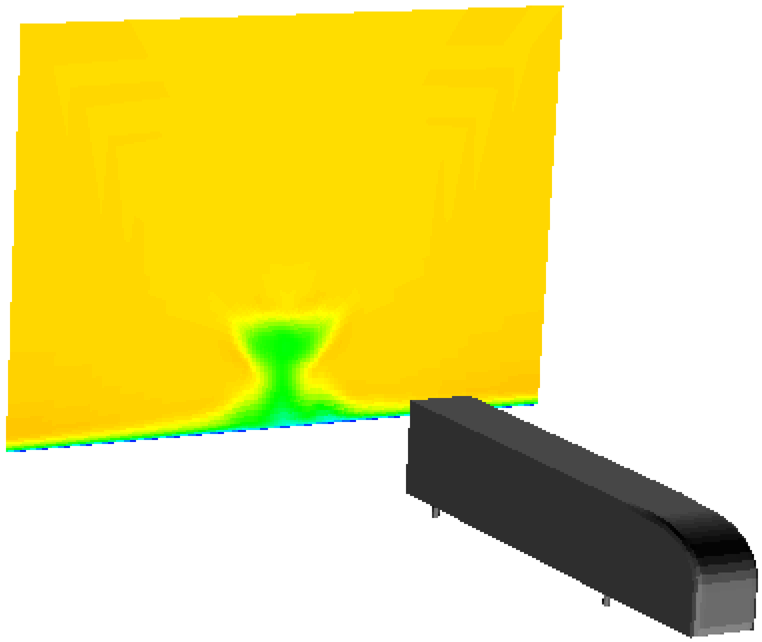
3 m from front of truck

Simulation results - time average flow field



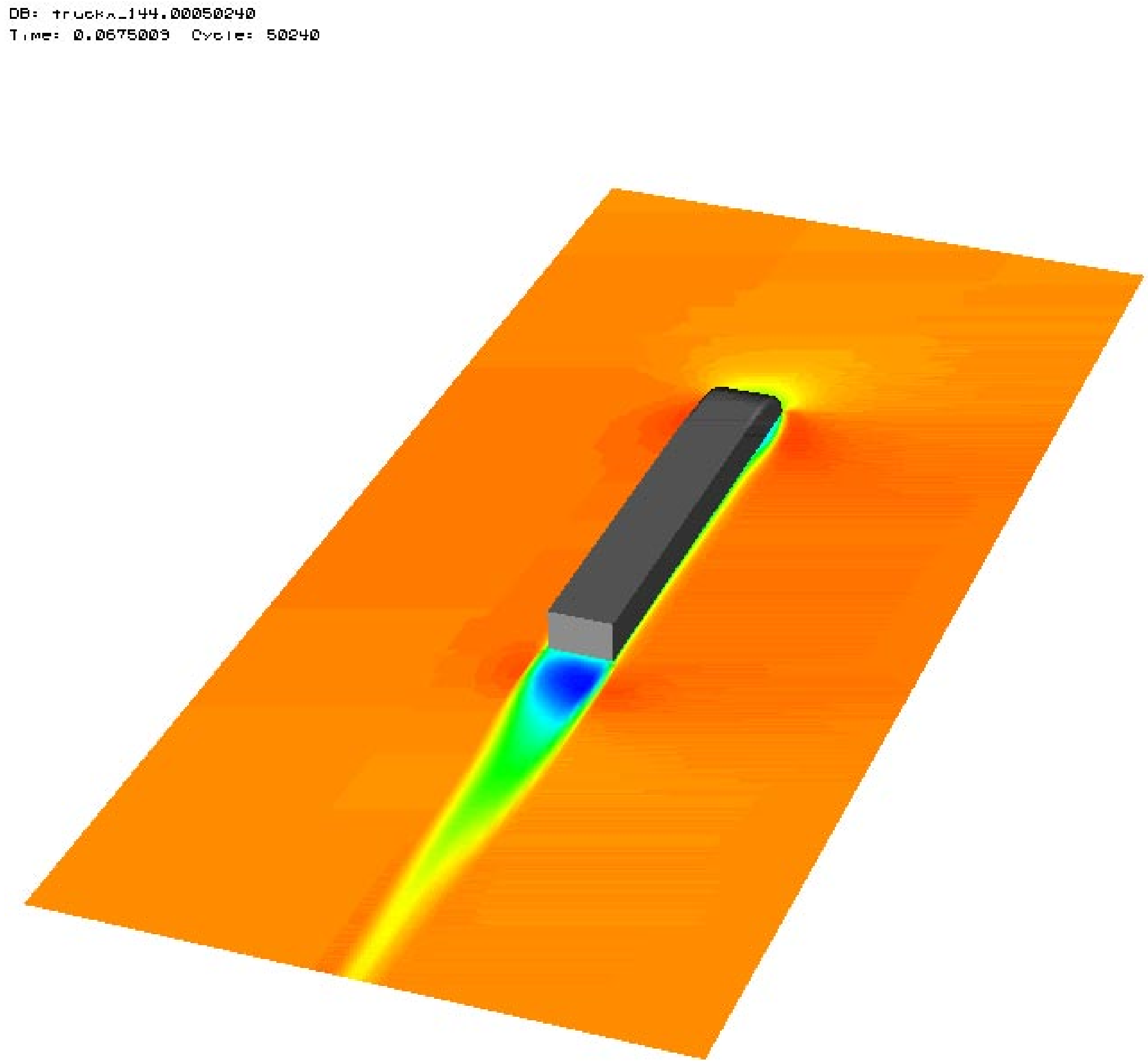
3.5 m from front of truck

Simulation results - time average flow field



4 m from front of truck

Simulation results - movie



Summary

A scalable grid has been created for the NASA 7’x10’ wind tunnel geometry

Compressible simulations for 0° yaw with 0.3 Million and 2.4 Million Element mesh in progress

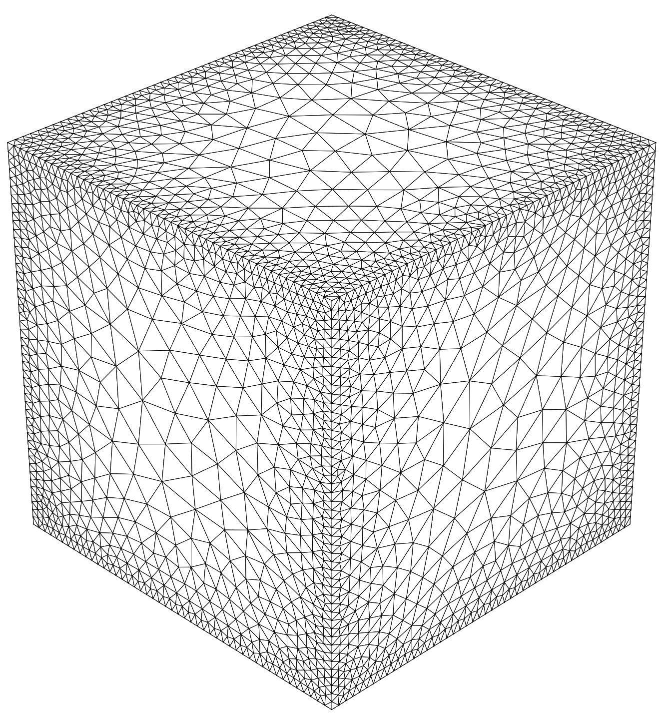
Simulation of Complex, Unsteady Flows Using a Grid-Free Vortex Method

A. Leonard
Graduate Aeronautical Laboratories
California Institute of Technology

M. Brady, L. Barba, M. Rubel

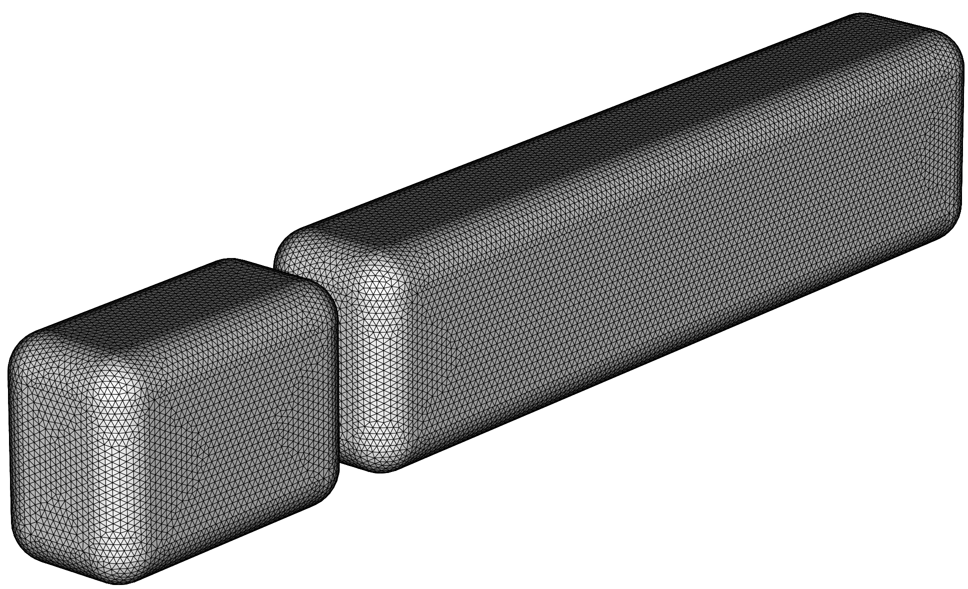
Vortex Code: Improvements

- Surface mesh adaptivity – triangles no longer restricted to particle size
- High order surface interpolants in progress
- Vortex particle size mapping function nearly complete



Vortex Code: Results

- Definition of GTS-scale geometry



- Tandem rounded cube (animation)
  $Re = 100$

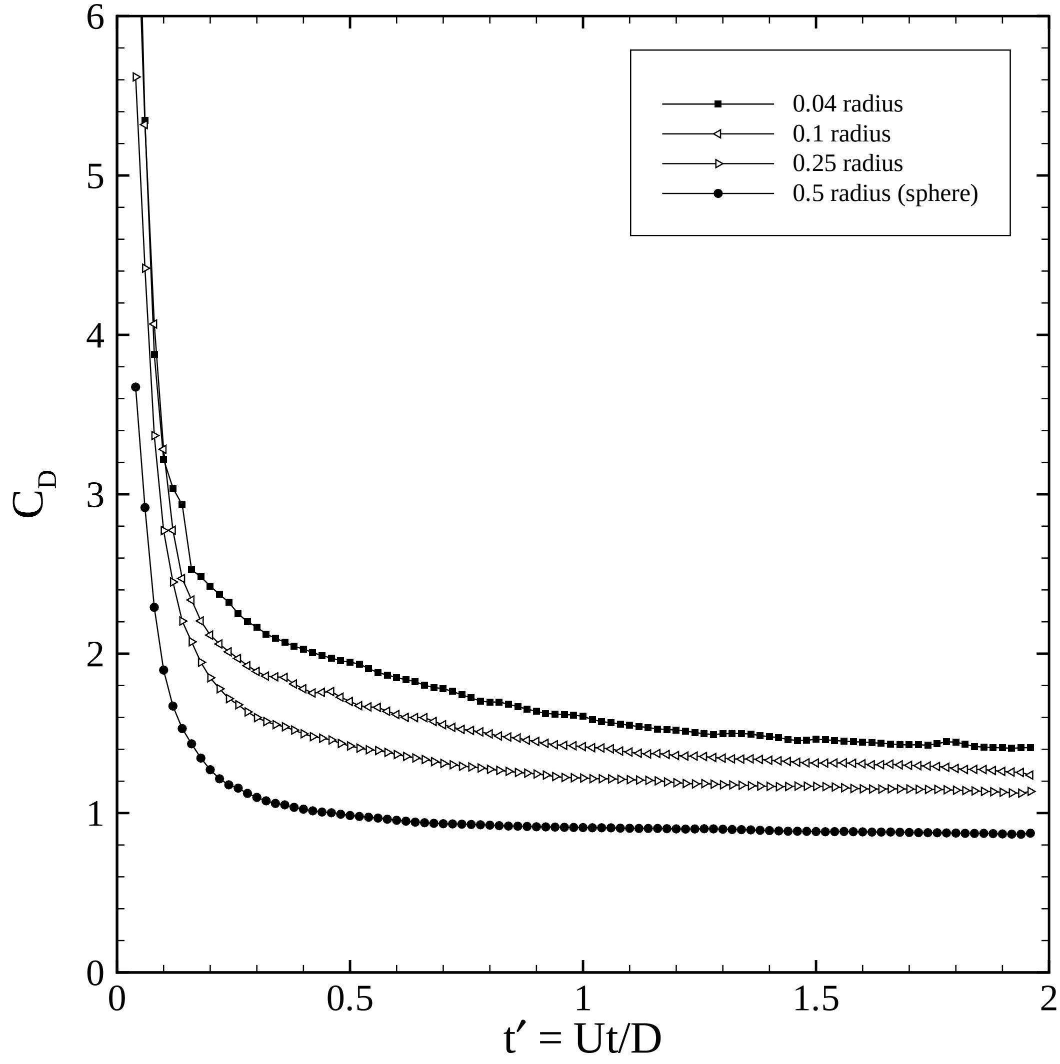
- Tandem rounded prism at GTS-scale (animation)
  $Re = 100$

Vortex Code: Verification

- Drag calculation via differentition of fluid impulse

$$C_D \propto \frac{d}{dt} \int_V x \times \omega \, dV$$

- Drag curves for sphere, rounded cubes, $Re = 100$



Large-eddy Simulation: Problem of High Re Wall Turbulence

- Length-scale near wall = Sqrt(viscosity/velocity gradient) – wall unit
- Large eddies near wall O(10 – 100) wall units
- LES grids 40 x 10 x 10 wall units near wall
- Pipe flow Re = 3 x 10**4 => R+ = 800

  # LES grid volumes = 5 x 10**5

  Pipe flow Re = 3 x 10**7 => R+ = 550,000

  # LES grid volumes = 5 x 10**11

  # grid volumes proportional to R+**2 = Re_tau**2

Wall layer SGS Models

- RANS for attached turbulent boundary layers, LES for wakes => DES (Spalart et al 1997)
- RANS for near-wall layer

  LES for outer turbulent boundary layer plus wakes
- Above with stochastic forcing of outer layer

  (LES or planetary boundary layers, Mason & Thomson, 1992)

Status / Future Work

- Incorporation of GTS model into full Vortex Method
- Implementation of the Vortex Method for arbitrary complex geometries
- Analysis of Reynolds number effects (leading edge curvature)
- Subgrid stress model for Large-Eddy Simulation

Ross Sheckler

Dynacs Engineering Co., Inc.

Industry Buy-in?

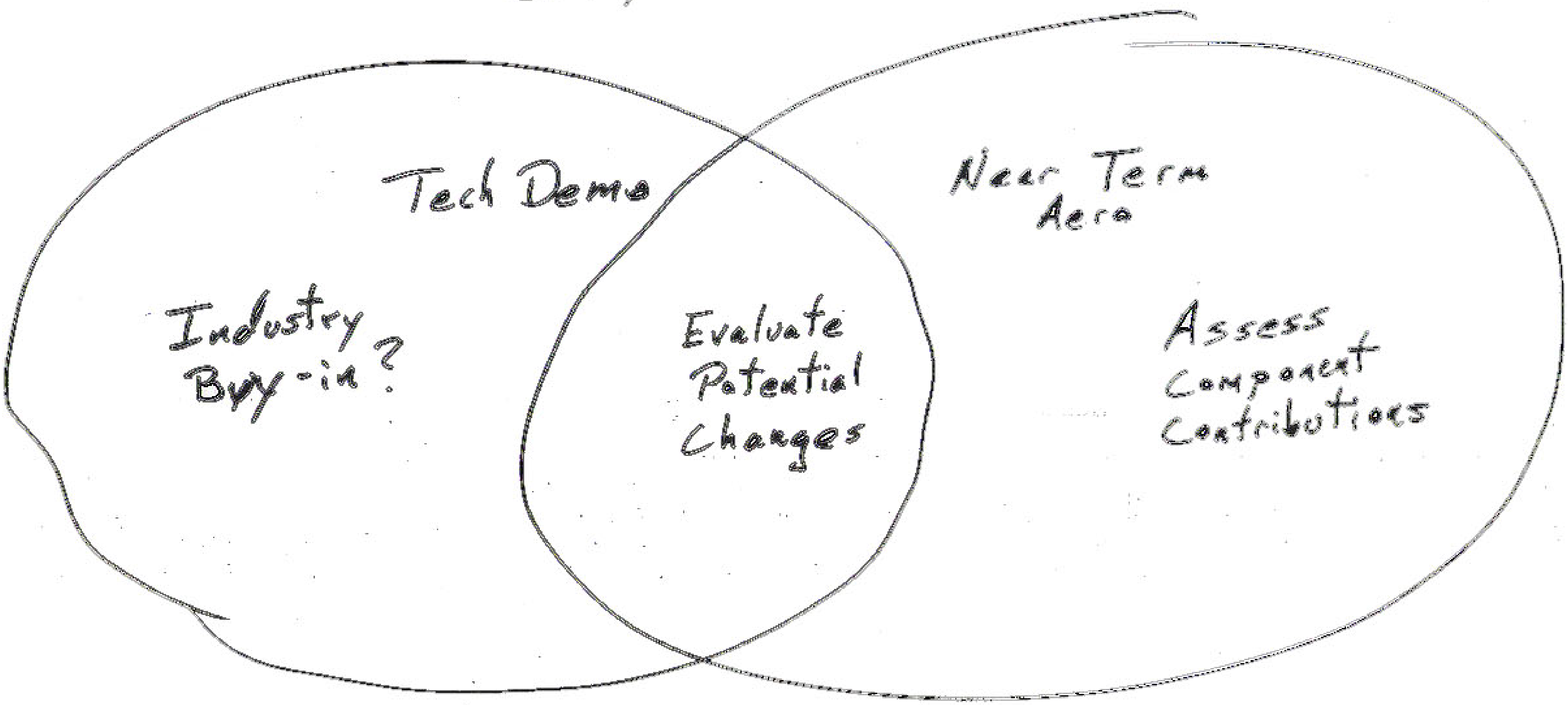
PACCAR J. Bectold - KW, C. Brewster - PB,
Keith Howard - Leyland, Martin de Louw - DAF,
Bob Morrison - PTC

Freightliner Luis Novoa, Gene Barron, ...

- USE TMA
- GO AFTER APPLICATION OF WHAT WE KNOW
  - LEGAL HURDLES
- SHOW HIGH TECH BENEFITS ~~IP~~ AFTER LEGAL HURDLES

- PROTOTYPING COST < $1 M

Demo/Near-Term

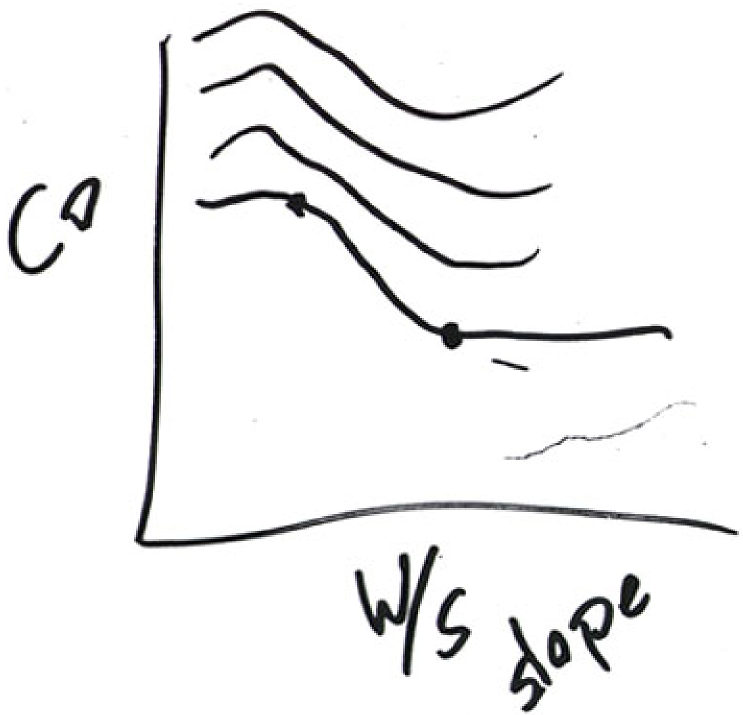


WHAT ARE THE AVAILABLE CANDIDATES?

- REMOVE MIRRORS
- WIDEN CAB
- CRUSHABLE BOAT-TAIL
- CRUSHABLE NOSE CONE
-
-
-
-

OTHER

- Wheel well tailoring
- Design guidelines
- C_D vs. trailer skirt ground clearance



W/S
hood
radii
taper